DOCUMENT RESUME

ED 345 949 SE 053 003

TITLE	Our Solar System at a Glance. Information Summaries.
INSTITUTION	National Aeronautics and Space Administration, Washington, D.C.
REPORT NO	NASA-PMS-010-A-(JPL)
PUB DATE	Jun 91
NOTE	37p.; Photographs may not reproduce clearly.
PUB TYPE	Guides - Classroom Use - Instructional Materials (For Learner) (051) -- Guides - Classroom Use - Teaching Guides (For Teacher) (052)
EDRS PRICE	MF01/PC02 Plus Postage.
DESCRIPTORS	*Instructional Materials; *Satellites (Aerospace); *Scientific and Technical Information; *Space Exploration; *Space Sciences
IDENTIFIERS	Comets; Moon; National Aeronautics and Space Administration; *Planets; Solar System; *Spacecraft; Sun

ABSTRACT

The United States has explored the solar system with automated spacecraft and human-crewed expeditions that have produced a quantum leap in our knowledge and understanding of the solar system. Through the electronic sight and other "senses" of our automated spacecraft, color and complexion have been given to worlds that for centuries appeared to eyes on Earth as fuzzy disks or indistinct points of light and dozens of previously unknown objects have been discovered. Following a categorical listing of 41 NASA unmanned spacecraft launched between 1959 to 1990, this NASA publication contains numerous photographs and presents factual summaries of the following: (1) the evolution of automated spacecraft; (2) current knowledge about the Sun including information on spacecraft that visited the Sun and future solar missions; (3) conditions on Mercury, especially information that was learned from the Mariner 10 spacecraft; (4) information on Venus as gleaned from Mariner 2, Mariner 5, the Pioneer Venus Orbiter, the Pioneer Venus Multiprobe, and Magellan spacecraft; (5) information about the Earth as learned from trips into space; (6) information about the moon, the Apollo program, and theories on the origin of the moon; (7) detailed information on Mars including information from spacecraft on its topography, prospects for harboring extraterrestrial life, and its two moons Phobos and Deimos; (8) research on asteroids and the results of meteoroid collisions with the earth; (9) data gathered on Jupiter and its moons Io, Europa, Ganymede and Callisto; (10) data on Saturn and its rings; (11) information on Uranus, its numerous icy moons including Miranda, Ariel, Umbriel, and Titania; (12) information on Neptune and its moons including Proteus and Nereid; (13) data concerning Pluto our most distant planet and its one moon Charon; and (14) information on the composition and orbits of comets including Halley's comet. A pictorial summary chart gives further information on the planets including mean distance from the sun, relative size, periods of revolution and rotation, inclination, eccentricity, and composition of their atmospheres. (PR)

NASA
National Aeronautics and
Space Administration

Information Summaries

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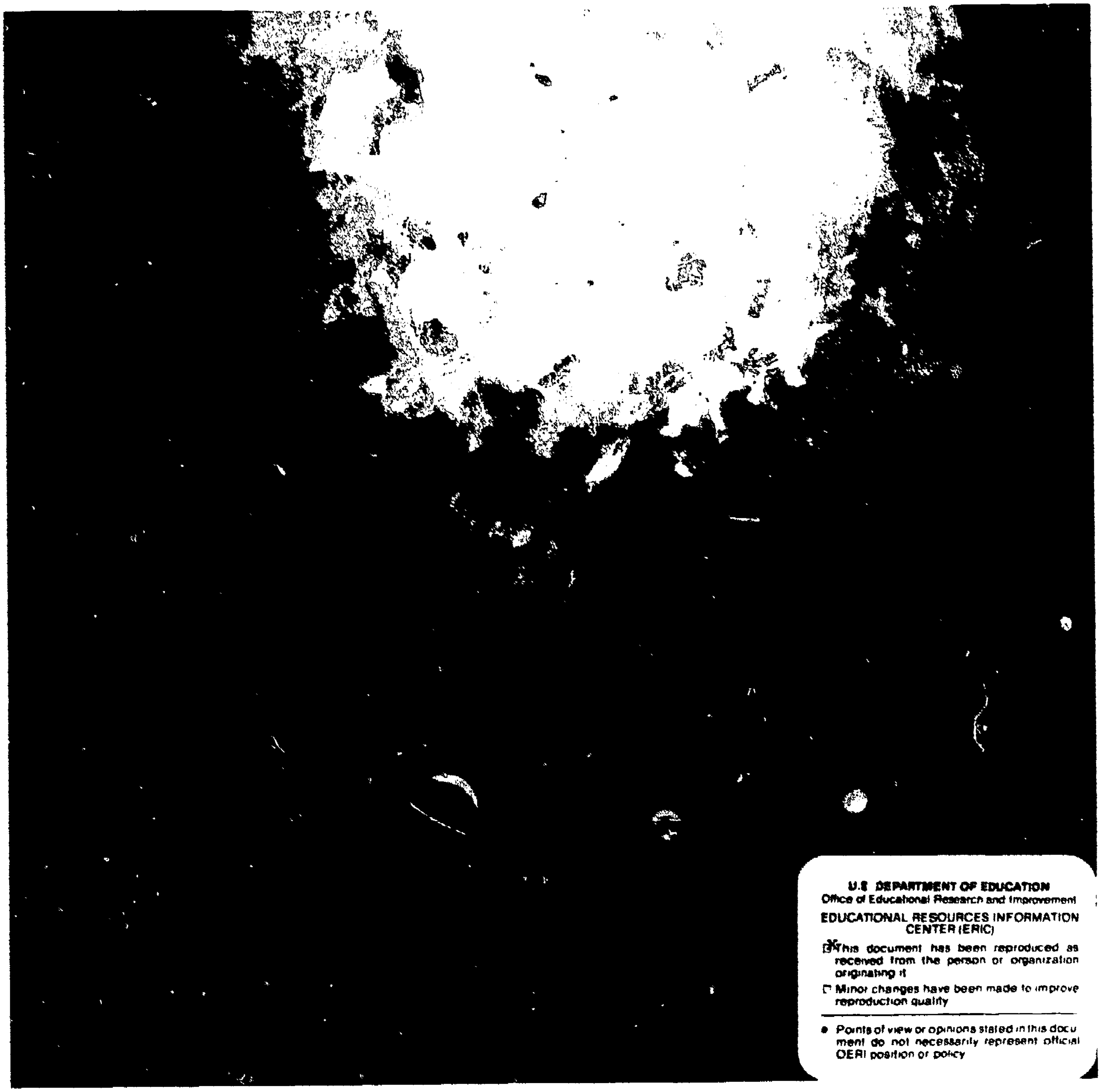
Our Solar System at a Glance



From our small world we have gazed upon the cosmic ocean for untold thousands of years. Ancient astronomers observed points of light that appeared to move among the stars. They called these objects planets, meaning wanderers, and named them after Roman deities — Jupiter, king of the gods; Mars, the god of war; Mercury, messenger of the gods; Venus, the god of love and beauty, and Saturn, father of Jupiter and god of agriculture. The stargazers also observed comets with sparkling tails, and meteors or shooting stars apparently falling from the sky.

Science flourished during the European Renaissance. Fundamental physical laws governing planetary motion were discovered, and the orbits of the planets around the Sun were calculated. In the 17th century, astronomers pointed a new device called the telescope at the heavens and made startling discoveries.

But the years since 1959 have amounted to a golden age of solar system exploration. Advancements in rocketry after World War II enabled our machines to break the grip of Earth's gravity and travel to the Moon and to other planets.

The United States has sent automated spacecraft, then human-crewed expeditions, to explore the Moon. Our automated machines have orbited and landed on Venus and Mars; explored the Sun's environment; observed comets, and made close-range surveys while flying past Mercury, Jupiter, Saturn, Uranus and Neptune.

These travelers brought a quantum leap in our knowledge and understanding of the solar system. Through the electronic sight and other "senses" of our automated spacecraft, color and complexion have been given to worlds that for centuries appeared to eyes on Earth as fuzzy disks or indistinct points of light. And dozens of previously unknown objects have been discovered.

Future historians will likely view these pioneering flights through the solar system as some of the most remarkable achievements of the 20th century.

Cover: The nine known planets and the Sun are drawn to scale size in this artist's rendering of our solar system. If the planets were actually the sizes shown, the average distance between the Sun and Pluto would be 550 meters (1,800 feet).

Contents

NASA's Automated Exploration of the Solar System

Spacecraft Launched Between 1959 and 1990

Pioneer

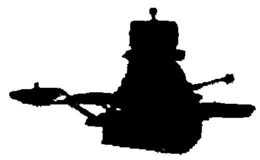
Mariner

Ranger

Spacecraft	Mission	Launch	Arrival	Results
Pioneer 4	Lunar flyby	3/3/59	3/4/59	Collected radiation data near Moon.
Pioneer 5	Solar orbit	3/11/60	N/A*	Data on radiation, particles & fields.
Mariner 2	Venus flyby	8/27/62	12/14/62	First craft to visit another planet.
Ranger 7	Lunar impact	7/28/64	7/31/64	Photo resolution 1,[illegible] of Earth-based images.
Mariner 4	Mars flyby	11/28/64	7/14/65	Data showed inhospitable world.
Ranger 8	Lunar impact	2/17/65	2/20/65	Impact in the Sea of Tranquility.
Ranger 9	Lunar impact	3/21/65	3/24/65	Photo resolution as fine as 0.25 meter (10 inches).
Pioneer 6	Solar orbit	12/16/65	N/A*	Data on the Sun & interplanetary space.
Surveyor 1	Lunar landing	5/30/66	6/2/66	Simulated Apollo flight & landing.
Lunar Orbiter 1	Lunar orbit	8/10/66	8/14/66	Found terrain rougher than expected.
Pioneer 7	Solar orbit	8/17/66	N/A*	Same as Pioneer 6.
Lunar Orbiter 2	Lunar orbit	11/6/66	11/10/66	Search for possible Apollo landing sites.
Lunar Orbiter 3	Lunar orbit	2/4/67	2/8/67	Mapped surface; examined gravitational field.
Surveyor 3	Lunar landing	4/17/67	4/20/67	Sampled soil; photographed [illegible].
Lunar Orbiter 4	Lunar polar orbit	5/4/67	5/8/67	Orbit allowed photos of polar regions.

*Spacecraft entered solar orbit immediately after leaving Earth.

Surveyor



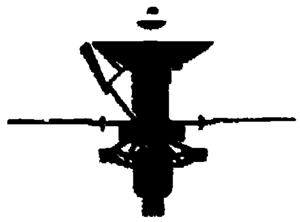
Lunar Orbiter

Viking

Spacecraft	Mission	Launch	Arrival	Results
Mariner 5	Venus flyby	6/14/67	10/19/67	Confirmed harsh surface conditions
Lunar Orbiter 5	Lunar polar orbit	8/1/67	8/5/67	Completed orbital mapping project.
Surveyor 5	Lunar landing	9/8/67	9/11/67	First chemical analysis of lunar soil.
Surveyor 6	Lunar landing	11/7/67	11/10/67	Three-dimensional photos.
Pioneer 8	Solar orbit	12/13/67	N/A*	Same as Pioneer 6.
Surveyor 7	Lunar landing	1/7/68	1/10/68	87,674 photos returned in Surveyor program.
Pioneer 9	Solar orbit	11/8/68	N/A*	Same as Pioneer 6.
Mariner 6	Mars flyby	2/24/69	7/31/69	Concentrated on equatorial region.
Mariner 7	Mars flyby	3/27/69	8/5/69	Concentrated on southern polar region.
Mariner 9	Mars orbit	5/30/71	11/13/71	Mapped entire planet & two moons.
Pioneer 10	Jupiter flyby	3/2/72	12/3/73	First examination of an outer planet.
Pioneer 11	Jupiter flyby Saturn flyby	4/5/73	12/2/74 9/1/79	Additional observations; used Jupiter's gravity to bend path to Saturn.
Mariner 10	Venus flyby Mercury flybys	11/3/73	2/5/74 3/29/74, 9/21/74 & 3/16/75	First photos of Venus; used Venus' gravity to bend path to Mercury. Three successful flybys imaged half of Mercury.
Helios 1	Solar orbit	12/10/74	N/A*	Orbited close to Sun. Helios was joint mission with Germany.

*Spacecraft entered solar orbit immediately after leaving Earth.

Voyager



Magellan

Galileo

Ulysses

Spacecraft	Mission	Launch	Arrival	Results
Viking 1	Mars orbit & landing	8/20/75	6/19/76 & 7/20/76	High-resolution photos; soil sampling.
Viking 2	Mars orbit & landing	9/9/75	8/7/76 & 9/3/76	Continued orbital & surface activity.
Helios 2	Solar orbit	1/15/76	N/A*	Continued solar studies of Helios 1.
Voyager 1	Jupiter flyby Saturn flyby	9/5/77	3/5/79 11/12/80	High-resolution images & [illegible] and moons.
Voyager 2	Jupiter flyby Saturn flyby Uranus flyby Neptune flyby	8/20/77	7/9/79 8/25/81 1/24/86 8/25/89	Additional observations. Voyager 1's success allowed retargeting of Voyager 2 at Saturn to point spacecraft to Uranus & Neptune. Flybys extremely successful.
Pioneer Venus Orbiter	Venus orbit	5/20/78	12/4/78	Detailed, long-term atmospheric observations; [illegible] mapping.
Pioneer Venus Multiprobe	Venus atmospheric probes	8/8/78	12/9/78	Main body & four probes profiled atmosphere.
International Sun-Earth Explorer 3 (ISEE-3)	Positioned between Earth & Sun	8/12/78	N/A*	[illegible]
International Cometary Explorer (ICE)	Comet Giacobini–Zinner flyby	N/A	9/11/85	Was ISEE 3 (see above). Renamed & retargeted to make first comet flyby.
Magellan	Venus orbit	[illegible]	8/10/90	High-resolution radar mapping.
Galileo	Jupiter orbit & atmospheric probe	10/18/89	12/7/95	Will make long-term observations of Jovian system.
Ulysses	Solar polar orbit	10/6/90	6–11/94 & 6–9/95	Will study the Sun's northern & southern polar regions.

*Spacecraft entered solar orbit immediately after leaving Earth.

Automated Spacecraft

The National Aeronautics and Space Administration's (NASA's) automated spacecraft for solar system exploration come in many shapes and sizes. While they are designed to fulfill separate and specific mission objectives, the craft share much in common.

Each spacecraft consists of various scientific instruments selected for a particular mission, supported by basic subsystems for electrical power, trajectory and orientation control, as well as for processing data and communicating with Earth.

Electrical power is required to operate the spacecraft instruments and systems. NASA uses both solar energy from arrays of photovoltaic cells and small nuclear generators to power its solar system missions. Rechargeable batteries are employed for backup and supplemental power.

Imagine that a spacecraft has successfully journeyed millions of miles through space to fly but one time near a planet, only to have its cameras and other sensing instruments pointed the wrong way as it speeds past the target! To help prevent such a mishap, a subsystem of small thrusters is used to control spacecraft.

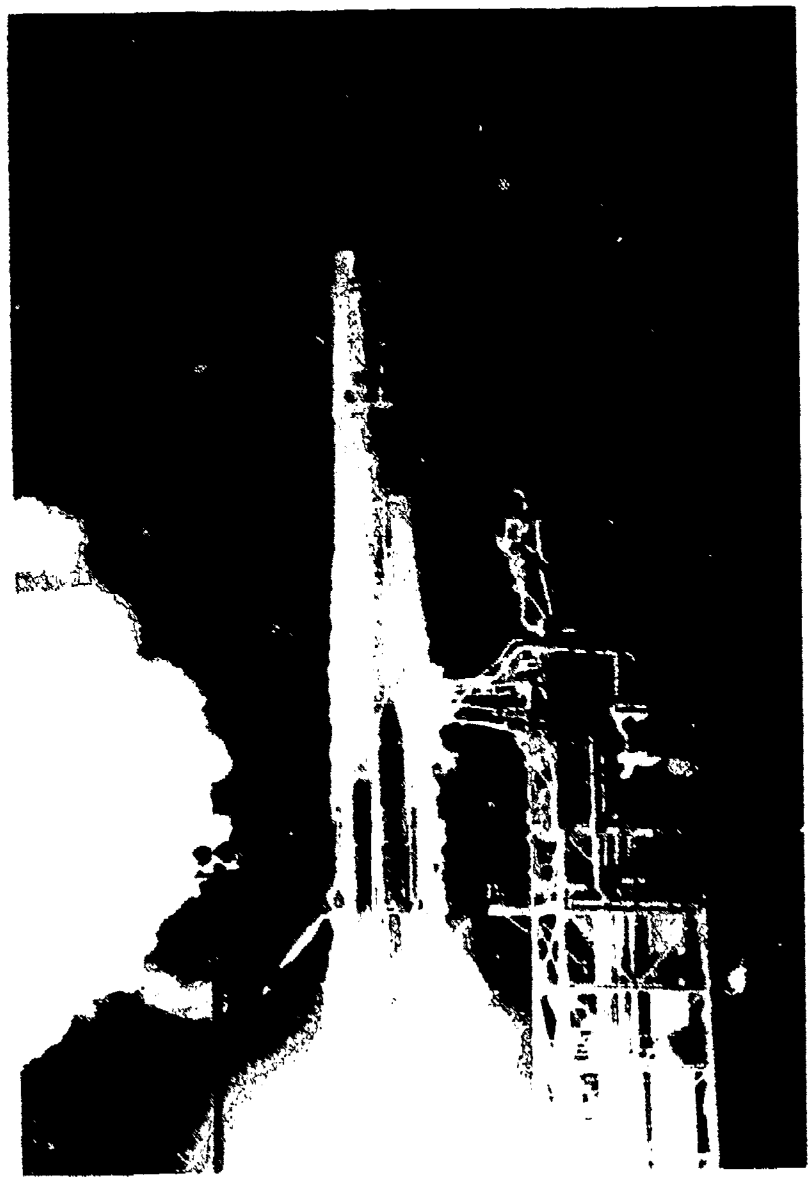
The thrusters are linked with devices that maintain a constant gaze at selected stars. Just as Earth's early seafarers used the stars to navigate the oceans, spacecraft use stars to maintain their bearings in space. With the subsystem locked onto fixed points of reference, flight controllers can keep a spacecraft's scientific instruments pointed at the target body and the craft's communications antennas pointed toward Earth. The thrusters can also be used to fine-tune the flight path and speed of the spacecraft to ensure that a target body is encountered at the planned distance and on the proper trajectory.

Between 1959 and 1971, NASA spacecraft were dispatched to study the Moon and the solar environment; they also scanned the inner planets other than Earth — Mercury, Venus and Mars. These three worlds, and our own, are known as the terrestrial planets because they share a solid-rock composition.

For the early planetary reconnaissance missions, NASA employed a highly successful series of spacecraft called the Mariners. Their flights helped shape the planning of later missions. Between 1962 and 1975, seven Mariner missions conducted the first surveys of our planetary neighbors in space.

All of the Mariners used solar panels as their primary power source. The first and the final versions of the spacecraft had two wings covered with photovoltaic cells. Other Mariners were equipped with four solar panels extending from their octagonal bodies.

Although the Mariners ranged from the Mariner 2 Venus spacecraft, weighing in at 203 kilograms (447 pounds), to the Mariner 9 Mars Orbiter, weighing in at 974 kilograms



Aboard an Atlas Centaur rocket, the Mariner 6 spacecraft lifts away from a launch pad at Cape Canaveral in Florida.

(2,147 pounds), their basic design remained quite similar throughout the program. The Mariner 5 Venus spacecraft, for example, had originally been a backup for the Mariner 4 Mars flyby. The Mariner 10 spacecraft sent to Venus and Mercury used components left over from the Mariner 9 Mars Orbiter program.

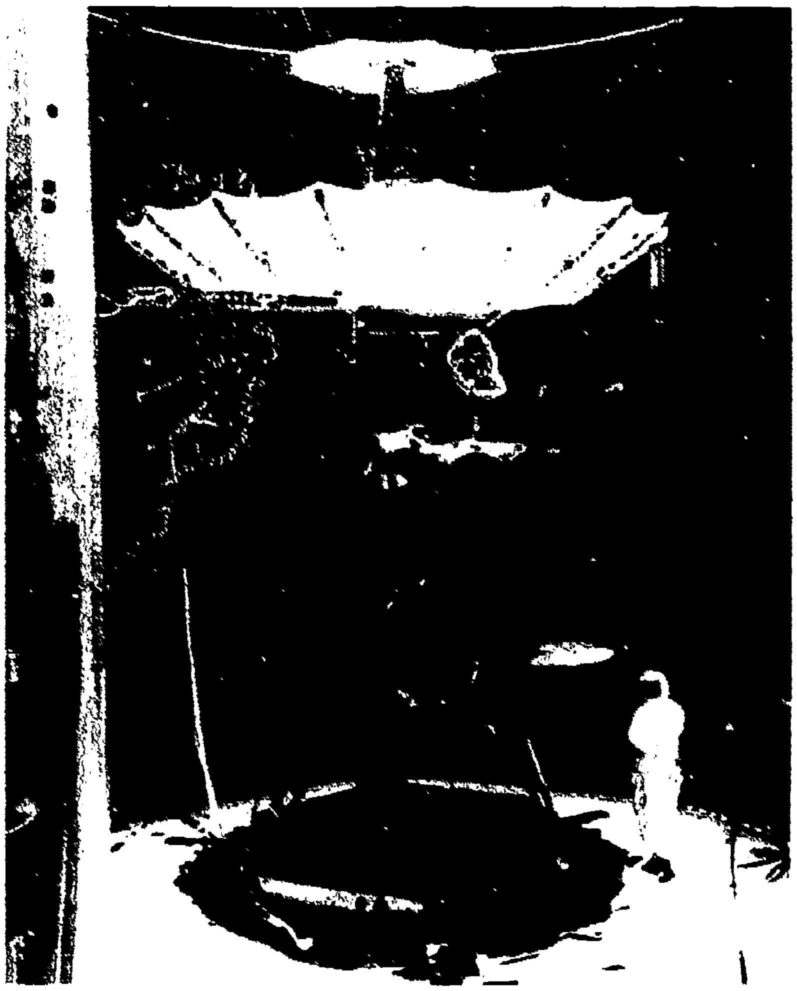
In 1972, NASA launched Pioneer 10, a Jupiter spacecraft. Interest was shifting to four of the outer planets — Jupiter, Saturn, Uranus and Neptune — giant balls of dense gas quite different from the terrestrial worlds we had already surveyed.

Four NASA spacecraft in all — two Pioneers and two Voyagers — were sent in the 1970s to tour the outer regions of our solar system. Because of the distances involved, these travelers took anywhere from 20 months to 12 years to reach their destinations. Barring faster spacecraft, they will eventually become the first human artifacts to journey to distant stars. Because the Sun's light becomes so faint in the outer solar system, these travelers do not use solar power but instead operate on electricity generated by heat from the decay of radioisotopes.

NASA also developed highly specialized spacecraft to revisit our neighbors Mars and Venus in the middle and late 1970s. Twin Viking Landers were equipped to serve as seismic and weather stations and as biology laboratories. Two advanced orbiters — descendants of the Mariner craft — carried the Viking Landers from Earth and then studied martian features from above.

Two drum-shaped Pioneer spacecraft visited Venus in 1978. The Pioneer Venus Orbiter was equipped with a radar instrument that allowed it to "see" through the planet's dense cloud cover to study surface features. The Pioneer Venus Multiprobe carried four probes that were dropped through the clouds. The probes and the main body — all of which contained scientific instruments — radioed information about the planet's atmosphere during their descent toward the surface.

A new generation of automated spacecraft — including Magellan, Galileo, Ulysses, Mars Observer, the Comet Rendezvous/Asteroid Flyby (CRAF) and Cassini — is being developed and sent out into the solar system to make detailed examinations that will increase our understanding of our neighborhood and our own planet.



Tests in a space simulator prepared the Galileo Orbiter for its six-year journey to Jupiter.

The Sun

A discussion of the objects in the solar system must start with the Sun. The Sun dwarfs the other bodies, representing approximately 99.86 percent of all the mass in the solar system; all of the planets, moons, asteroids, comets, dust and gas add up to only about 0.14 percent. This 0.14 percent represents the material left over from the Sun's formation. One hundred and nine Earths would be required to fit across the Sun's disk, and its interior could hold over 1.3 million Earths.

As a star, the Sun generates energy by the process of fusion. The temperature at the Sun's core is 15 million degrees Celsius (27 million degrees Fahrenheit), and the pressure there is 340 billion times Earth's air pressure at sea level. The Sun's surface temperature of 5,500 degrees Celsius (10,000 degrees Fahrenheit) seems almost chilly compared to its core temperature! At the solar core, hydrogen can fuse into helium, producing energy. The Sun also produces a strong magnetic field and streams of charged particles, the field and streams extending far beyond the planets.

The Sun appears to have been active for 4.6 billion years and has enough fuel for another five billion years or so. At the end of its life, the Sun will start to fuse helium into heavier elements and begin to swell up, ultimately growing so large that it will swallow Earth. After a billion years as a "red giant," it will suddenly collapse into a "white dwarf" — the final end product of a star like ours. It may take a *trillion* years to cool off completely.

Many spacecraft have explored the Sun's environment, but none have gotten any closer to its surface than approximately two-thirds of the distance from Earth to the Sun. Pioneers 5–11, the Pioneer Venus Orbiter, Voyagers 1 and 2 and other spacecraft have all sampled the solar environment. The Ulysses spacecraft, launched on October 6, 1990, is a joint solar mission of NASA and the European Space Agency. After using Jupiter's gravity to change its trajectory, Ulysses will fly over the Sun's polar regions during 1994 and 1995 and will perform a wide range of studies using nine onboard scientific instruments.

We are fortunate that the Sun is exactly the way it is. If it were different in almost any way, life would almost certainly never have developed on Earth.

Turbulent helium gas on and near the Sun is visible in this ultraviolet-light photograph taken by astronauts on Skylab, an Earth-orbiting space station, in June 1973.

Mercury

Obtaining the first close-up views of Mercury was the primary objective of the Mariner 10 spacecraft, launched on November 3, 1973, from Kennedy Space Center in Florida. After a journey of nearly five months, including a flyby of Venus, the spacecraft passed within 703 kilometers (437 miles) of the solar system's innermost planet on March 29, 1974.

Until Mariner 10, little was known about Mercury. Even the best telescopic views from Earth showed Mercury as an indistinct object lacking any surface detail. The planet is so close to the Sun that it is usually lost in solar glare. When the planet is visible on Earth's horizon just after sunset or before dawn, it is obscured by the haze and dust in our atmosphere. Only radar telescopes gave any hint of Mercury's surface conditions prior to the voyage of Mariner 10.

The photographs Mariner 10 radioed back to Earth revealed an ancient, heavily cratered surface, closely resembling our own Moon. The pictures also showed huge cliffs crisscrossing the planet. These apparently were created when Mercury's interior cooled and shrank, buckling the planet's crust. The cliffs are as high as 3 kilometers (2 miles) and as long as 500 kilometers (310 miles).

Instruments on Mariner 10 discovered that Mercury has a weak magnetic field and a trace of atmosphere — a trillionth the density of Earth's atmosphere and composed chiefly of argon, neon and helium. When the planet's orbit takes it closest to the Sun, surface temperatures range from 467 degrees Celsius (872 degrees Fahrenheit) on Mercury's sunlit side to -183 degrees Celsius (-298 degrees Fahrenheit) on the dark side. This range in surface temperature — 650 degrees Celsius (1,170 degrees Fahrenheit) — is the largest for a single body in the solar system. Mercury literally bakes and freezes at the same time.

Days and nights are long on Mercury. The combination of a slow rotation relative to the stars (59 Earth days) and a rapid revolution around the Sun (88 Earth days) means that one Mercury solar day takes 176 Earth days or two Mercury years — the time it takes the innermost planet to complete two orbits around the Sun!

Mercury appears to have a crust of light silicate rock like that of Earth. Scientists believe Mercury has a heavy iron-rich core making up slightly less than half of its volume. That would make Mercury's core larger, proportionally, than the Moon's core or those of any of the planets.

After the initial Mercury encounter, Mariner 10 made two additional flybys — on September 21, 1974, and March 16, 1975 — before control gas used to orient the spacecraft was exhausted and the mission was concluded. Each flyby took place at the same local Mercury time when the identical half of the planet was illuminated; as a result, we still have not seen one-half of the planet's surface.

Mercury's Caloris Planitia (left) is a basin formed by a massive impact; semicircular ridges are visible. The rest of the basin, including the center, is hidden in shadow.

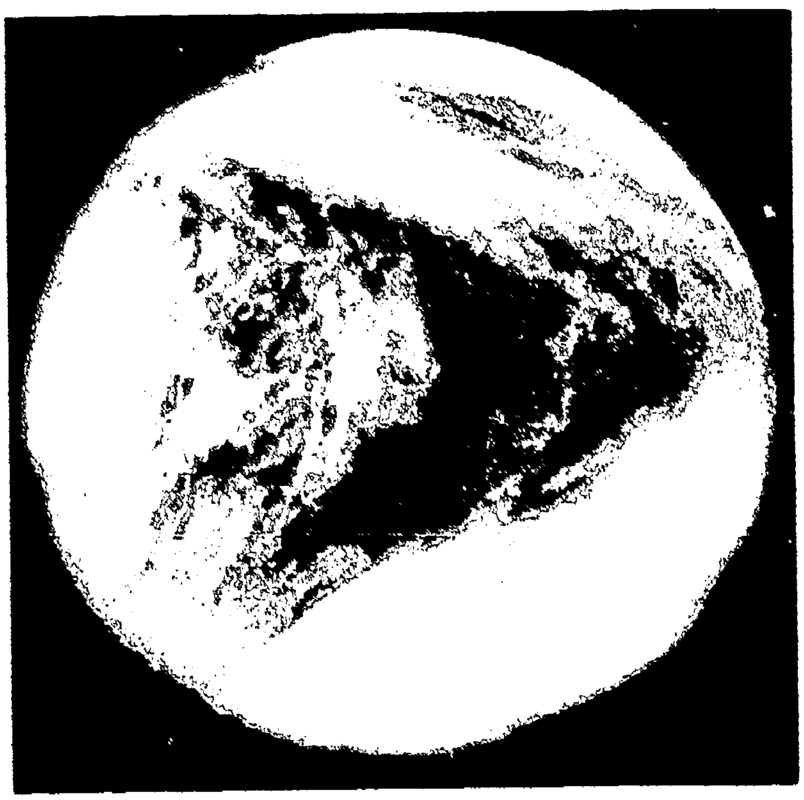
11

Venus

Veiled by dense cloud cover, Venus — our nearest planetary neighbor — was the first planet to be explored. The Mariner 2 spacecraft, launched on August 27, 1962, was the first of more than a dozen successful American and Soviet missions to study the mysterious planet. As spacecraft flew by or orbited Venus, plunged into the atmosphere or gently landed on Venus' surface, romantic myths and speculations about our neighbor were laid to rest.

On December 14, 1962, Mariner 2 passed within 34,839 kilometers (21,648 miles) of Venus and became the first spacecraft to scan another planet; onboard instruments measured Venus for 42 minutes. Mariner 5, launched in June 1967, flew much closer to the planet. Passing within 4,094 kilometers (2,544 miles) of Venus on the second American flyby, Mariner 5's instruments measured the planet's magnetic field, ionosphere, radiation belts and temperatures. On its way to Mercury, Mariner 10 flew by Venus and transmitted ultraviolet pictures to Earth showing cloud circulation patterns in the Venusian atmosphere.

In the spring and summer of 1978, two spacecraft were launched to further unravel the mysteries of Venus. On December 4 of the same year, one of these travelers — the Pioneer Venus Orbiter — became the first spacecraft placed in orbit around the planet.



The circulation of Venus' dense atmosphere is discernible in this enhanced photograph from the Pioneer Venus Orbiter.

Five days later, the five separate components making up the second spacecraft — the Pioneer Venus Multiprobe — entered the Venusian atmosphere at different locations above the planet. The four small, independent probes and the main body radioed atmospheric data back to Earth during their descent toward the surface. Although designed to examine the atmosphere, one of the probes survived its impact with the surface and continued to transmit data for another hour.

Venus resembles Earth in size, physical composition and density more closely than any other known planet. However, spacecraft have discovered significant differences as well. For example, Venus' rotation (west to east) is retrograde (backward) compared to the east-to-west spin of Earth and most of the other planets.

Approximately 96.5 percent of Venus' atmosphere (95 times as dense as Earth's) is carbon dioxide. The principal constituent of Earth's atmosphere is nitrogen. Venus' atmosphere acts like a greenhouse, permitting solar radiation to reach the surface but trapping the heat that would ordinarily be radiated back into space. As a result, the planet's average surface temperature is 482 degrees Celsius (900 degrees Fahrenheit), hot enough to melt lead.

A radio altimeter on the Pioneer Venus Orbiter provided the first means of seeing through the planet's dense cloud cover and determining surface features over almost the entire planet. NASA's Magellan spacecraft, launched on May 5, 1989, has orbited Venus since August 10, 1990. The spacecraft uses radar-mapping techniques to provide ultrahigh-resolution images of the surface.

Magellan has revealed a landscape dominated by volcanic features, faults and impact craters. Huge areas of the surface show evidence of multiple periods of lava flooding with flows lying on top of previous ones. An elevated region named Ishtar Terra is a lava-filled basin as large as the United States. At one end of this plateau sits Maxwell Montes, a mountain the size of Mount Everest. Scarring the mountain's flank is a 100-kilometer (62-mile) wide, 2.5-kilometer (1.5-mile) deep impact crater named Cleopatra. (Almost all features on Venus are named for women; Maxwell Montes, Alpha Regio and Beta Regio are the exceptions.) Craters survive on Venus for perhaps 400 million years because there is no water and very little wind erosion.

Extensive fault-line networks cover the planet, probably the result of the same crustal flexing that produces plate tectonics on Earth. But on Venus the surface temperature is sufficient to weaken the rock, which cracks just about everywhere, preventing the formation of major plates and large earthquake faults like the San Andreas Fault in California.

Venus' predominant weather pattern is a high-altitude, high-speed circulation of clouds that contain sulfuric acid

At speeds reaching as high as 360 kilometers (225 miles) per hour, the clouds circle the planet in only four Earth days. The circulation is in the same direction — west to east — as Venus' slow rotation of 243 Earth days, whereas Earth's winds blow in both directions — west to east and east to west — in six alternating bands. Venus' atmosphere serves as a simplified laboratory for the study of our weather.

Three large impact craters and numerous faults appear in this Magellan radar mosaic of Venus' surface. The largest crater has a diameter of 50 kilometers (31 miles). The entire area shown is 550 kilometers (342 miles) wide and 500 kilometers (310 miles) long.

Earth

As viewed from space, our world's distinguishing characteristics are its blue waters, brown and green land masses and white clouds. We are enveloped by an ocean of air consisting of 78 percent nitrogen, 21 percent oxygen and 1 percent other constituents. The only planet in the solar system known to harbor life, Earth orbits the Sun at an average distance of 150 million kilometers (93 million miles). Earth is the third planet from the Sun and the fifth largest in the solar system, with a diameter just a few hundred kilometers larger than that of Venus.

Our planet's rapid spin and molten nickel-iron core give rise to an extensive magnetic field, which, along with the atmosphere, shields us from nearly all of the harmful radiation coming from the Sun and other stars. Earth's atmosphere protects us from meteors as well, most of which burn up before they can strike the surface. Active geological processes have left no evidence of the pelting Earth almost certainly received soon after it formed — about 4.6 billion years ago. Along with the other newly formed planets, it was showered by space debris in the early days of the solar system.

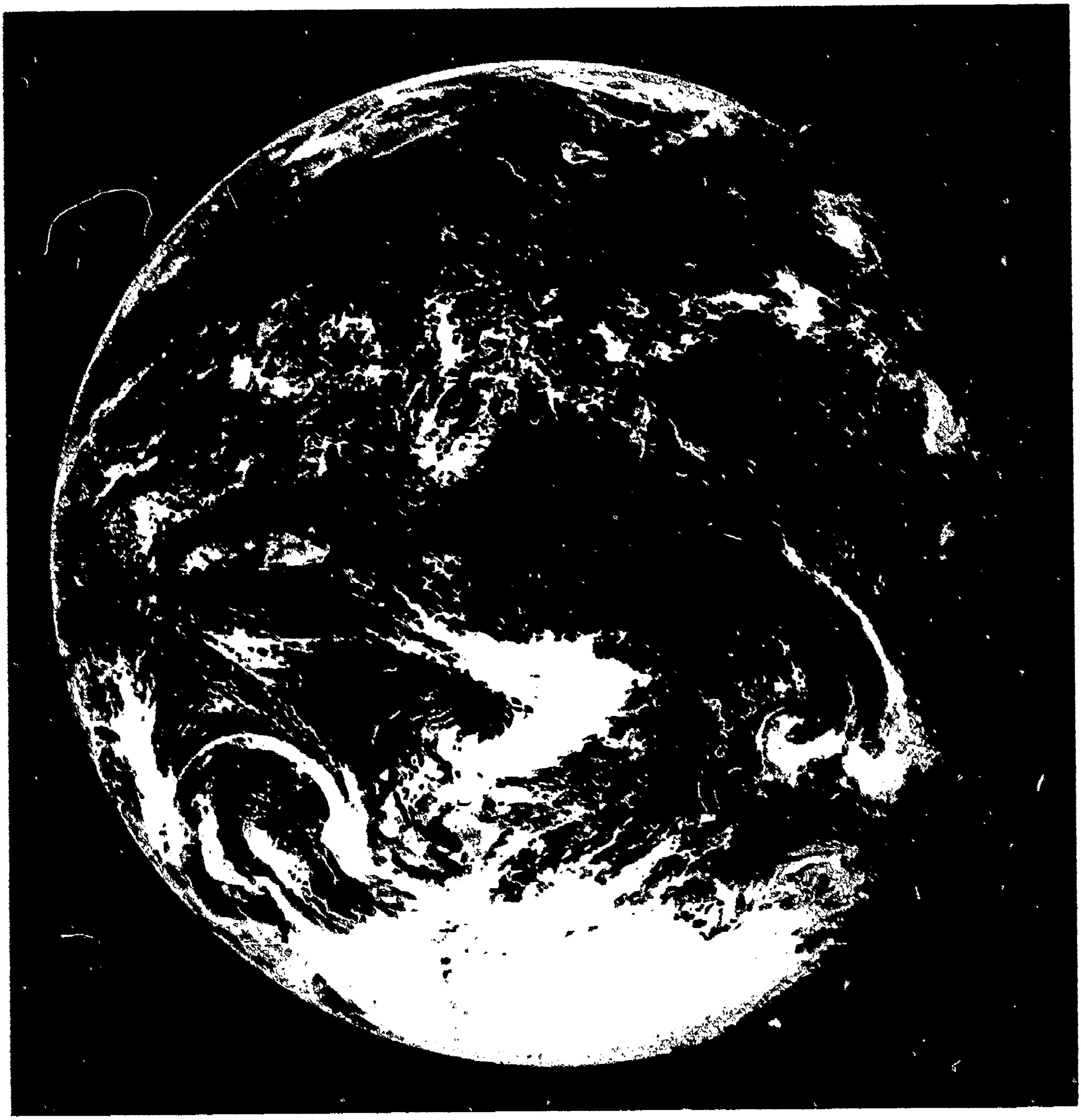
From our journeys into space, we have learned much about our home planet. The first American satellite — Explorer 1 — was launched from Cape Canaveral in Florida on January 31, 1958, and discovered an intense radiation zone, now called the Van Allen radiation belts, surrounding Earth.

Since then, other research satellites have revealed that our planet's magnetic field is distorted into a tear-drop shape by the solar wind — the stream of charged particles continuously ejected from the Sun. We've learned that the magnetic field does not fade off into space but has definite boundaries. And we now know that our wispy upper atmosphere, once believed calm and uneventful, seethes with activity — swelling by day and contracting by night. Affected by changes in solar activity, the upper atmosphere contributes to weather and climate on Earth.

Besides affecting Earth's weather, solar activity gives rise to a dramatic visual phenomenon in our atmosphere. When charged particles from the solar wind become trapped in Earth's magnetic field, they collide with air molecules above our planet's magnetic poles. These air molecules then begin to glow and are known as the auroras or the northern and southern lights.

Satellites about 35,789 kilometers (22,238 miles) out in space play a major role in daily local weather forecasting. These watchful electronic eyes warn us of dangerous storms. Continuous global monitoring provides a vast amount of useful data and contributes to a better understanding of Earth's complex weather systems.

From their unique vantage points, satellites can survey Earth's oceans, land use and resources, and monitor the planet's health. These eyes in space have saved countless lives, provided tremendous conveniences and shown us that we may be altering our planet in dangerous ways.



Our planet Earth, the solar system's only known oasis of life, was photographed by the Apollo 17 astronauts.

The Moon

The Moon is Earth's single natural satellite. The first human footsteps on an alien world were made by American astronauts on the dusty surface of our airless, lifeless companion. In preparation for the human-crewed Apollo expeditions, NASA dispatched the automated Ranger, Surveyor and Lunar Orbiter spacecraft to study the Moon between 1964 and 1968.

NASA's Apollo program left a large legacy of lunar materials and data. Six two-astronaut crews landed on and explored the lunar surface between 1969 and 1972, carrying back a collection of rocks and soil weighing a total of 382 kilograms (842 pounds) and consisting of more than 2,000 separate samples.

From this material and other studies, scientists have constructed a history of the Moon that includes its infancy. Rocks collected from the lunar highlands date to about 4.0–4.3 billion years old. The first few million years of the Moon's existence were so violent that few traces of this period remain. As a molten outer layer gradually cooled and solidified into different kinds of rock, the Moon was bombarded by huge asteroids and smaller objects. Some of the asteroids were as large as Rhode Island or Delaware, and their collisions with the Moon created basins hundreds of kilometers across.

This catastrophic bombardment tapered off approximately four billion years ago, leaving the lunar highlands covered with huge, overlapping craters and a deep layer of shattered and broken rock. Heat produced by the decay of radioactive elements began to melt the interior of the Moon at depths of about 200 kilometers (125 miles) below the surface. Then, for the next 700 million years — from about 3.8 to 3.1 billion years ago — lava rose from inside the Moon. The lava gradually spread out over the surface, flooding the large impact basins to form the dark areas that Galileo Galilei, an astronomer of the Italian Renaissance, called *maria*, meaning seas.

As far as we can tell, there has been no significant volcanic activity on the Moon for more than three billion years. Since then, the lunar surface has been altered only by micrometeorites, by the atomic particles from the Sun and stars, by the rare impacts of large meteorites and by spacecraft and astronauts. If our astronauts had landed on the Moon a billion years ago, they would have seen a landscape very similar to the one today. Thousands of years from now, the footsteps left by the Apollo crews will remain sharp and clear.

The origin of the Moon is still a mystery. Four theories attempt an explanation: the Moon formed near Earth as a separate body; it was torn from Earth; it formed somewhere else and was captured by our planet's gravity, or it was the result of a collision between Earth and an asteroid about the size of Mars. The last theory has some good support but is far from certain.

Apollo 12 astronauts landed on the lunar surface within walking distance of Surveyor 3, a feat made possible by the photographic skill of Lunar Orbiter 3.

15

Mars

Of all the planets, Mars has long been considered the solar system's prime candidate for harboring extraterrestrial life. Astronomers studying the red planet through telescopes saw what appeared to be straight lines crisscrossing its surface. These observations — later determined to be optical illusions — led to the popular notion that intelligent beings had constructed a system of irrigation canals on the planet. In 1938, when Orson Welles broadcast a radio drama based on the science fiction classic *War of the Worlds* by H.G. Wells, enough people believed in the tale of invading martians to cause a near panic.

Another reason for scientists to expect life on Mars had to do with the apparent seasonal color changes on the planet's surface. This phenomenon led to speculation that conditions might support a bloom of martian vegetation during the warmer months and cause plant life to become dormant during colder periods.

So far, six American missions to Mars have been carried out. Four Mariner spacecraft — three flying by the planet and one placed into martian orbit — surveyed the planet extensively before the Viking Orbiters and Landers arrived.

Mariner 4, launched in late 1964, flew past Mars on July 14, 1965, within 9,846 kilometers (6,118 miles) of the surface. Transmitting to Earth 22 close-up pictures of the planet, the spacecraft found many craters and naturally occurring channels but no evidence of artificial canals or flowing water. Mariners 6 and 7 followed with their flybys during the summer of 1969 and returned 201 pictures. Mariners 4, 6 and 7 showed a diversity of surface conditions as well as a thin, cold, dry atmosphere of carbon dioxide.

On May 30, 1971, the Mariner 9 Orbiter was launched on a mission to make a year-long study of the martian surface. The spacecraft arrived five and a half months after liftoff, only to find Mars in the midst of a planet-wide dust

Earth's hurricanes and typhoons are powered by differences in atmospheric temperatures and pressures. Similar weather conditions occur on Mars, Jupiter, Saturn and Neptune. Compare Earth's Pacific storm (A) with a martian cyclone (B) and Jupiter's Great Red Spot (C) — all are circular storm systems.

16

storm that made surface photography impossible for several weeks. But after the storm cleared, Mariner 9 began returning the first of 7,329 pictures; these revealed previously unknown martian features, including evidence that large amounts of water once flowed across the surface, etching river valleys and flood plains.

In August and September 1975, the Viking 1 and 2 spacecraft — each consisting of an orbiter and a lander — lifted off from Kennedy Space Center. The mission was designed to answer several questions about the red planet, including, Is there life there? Nobody expected the spacecraft to spot martian cities, but it was hoped that the biology experiments on the Viking Landers would at least find evidence of primitive life — past or present.

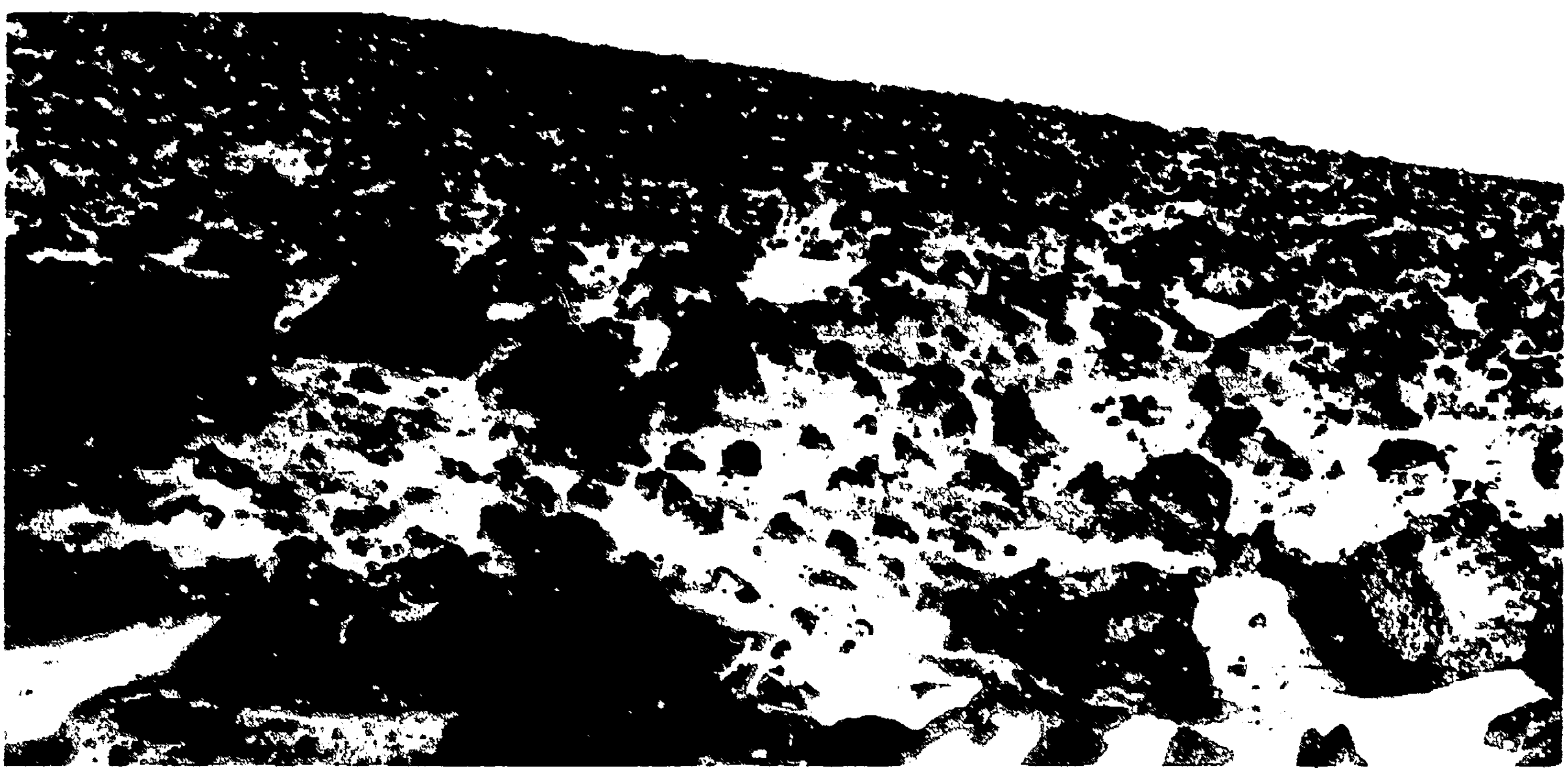
Viking Lander 1 became the first spacecraft to successfully touch down on another planet when it landed on July 20, 1976, while the United States was celebrating its Bicentennial. Photographs sent back from Chryse Planitia ("Plains of Gold") showed a bleak, rusty-red landscape. Panoramic images returned by Viking Lander 1 revealed a rolling plain, littered with rocks and marked by rippled sand dunes. Fine red dust from the martian soil gives the sky a salmon hue. When Viking Lander 2 touched down on Utopia Planitia on September 3, 1976, it viewed a more rolling landscape than the one seen by its predecessor — one without visible dunes.

The results sent back by the laboratory on each Viking Lander were inconclusive. Small samples of the red martian soil were tested in three different experiments designed to detect biological processes. While some of the test results seemed to indicate biological activity, later analysis confirmed that this activity was inorganic in nature and related to the planet's soil chemistry. Is there life on Mars? No one knows for sure, but the Viking mission found no evidence that organic molecules exist there.

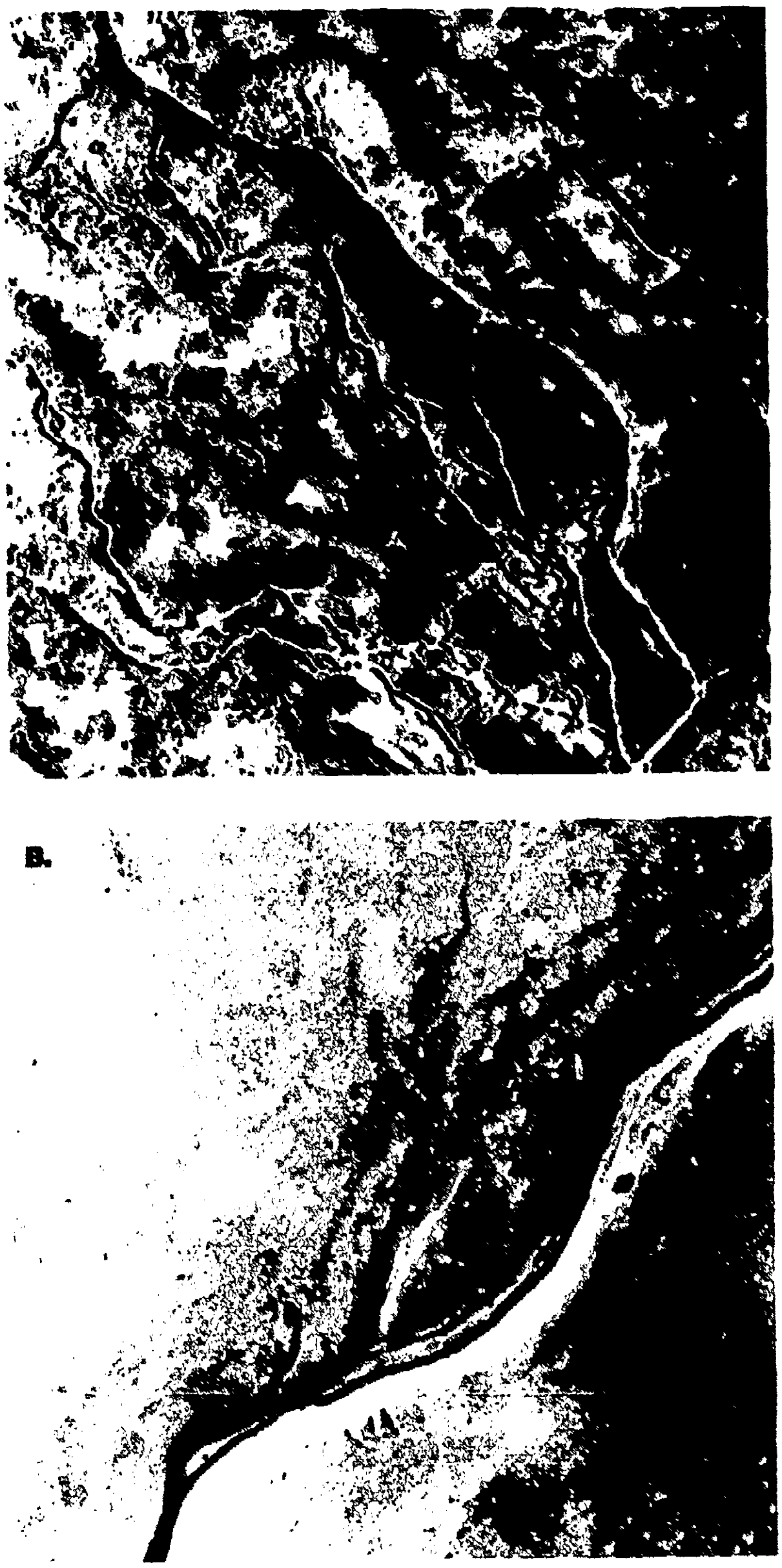
The Viking Landers became weather stations, recording wind velocity and direction as well as atmospheric temperature and pressure. Few weather changes were observed. The highest temperature recorded by either spacecraft was –14 degrees Celsius (7 degrees Fahrenheit) at the Viking Lander 1 site in midsummer.

The lowest temperature, –120 degrees Celsius (–184 degrees Fahrenheit), was recorded at the more northerly Viking Lander 2 site during winter. Near-hurricane wind speeds were measured at the two martian weather stations during global dust storms, but because the atmosphere is so thin, wind force is minimal. Viking Lander 2 photographed light patches of frost — probably water-ice — during its second winter on the planet.

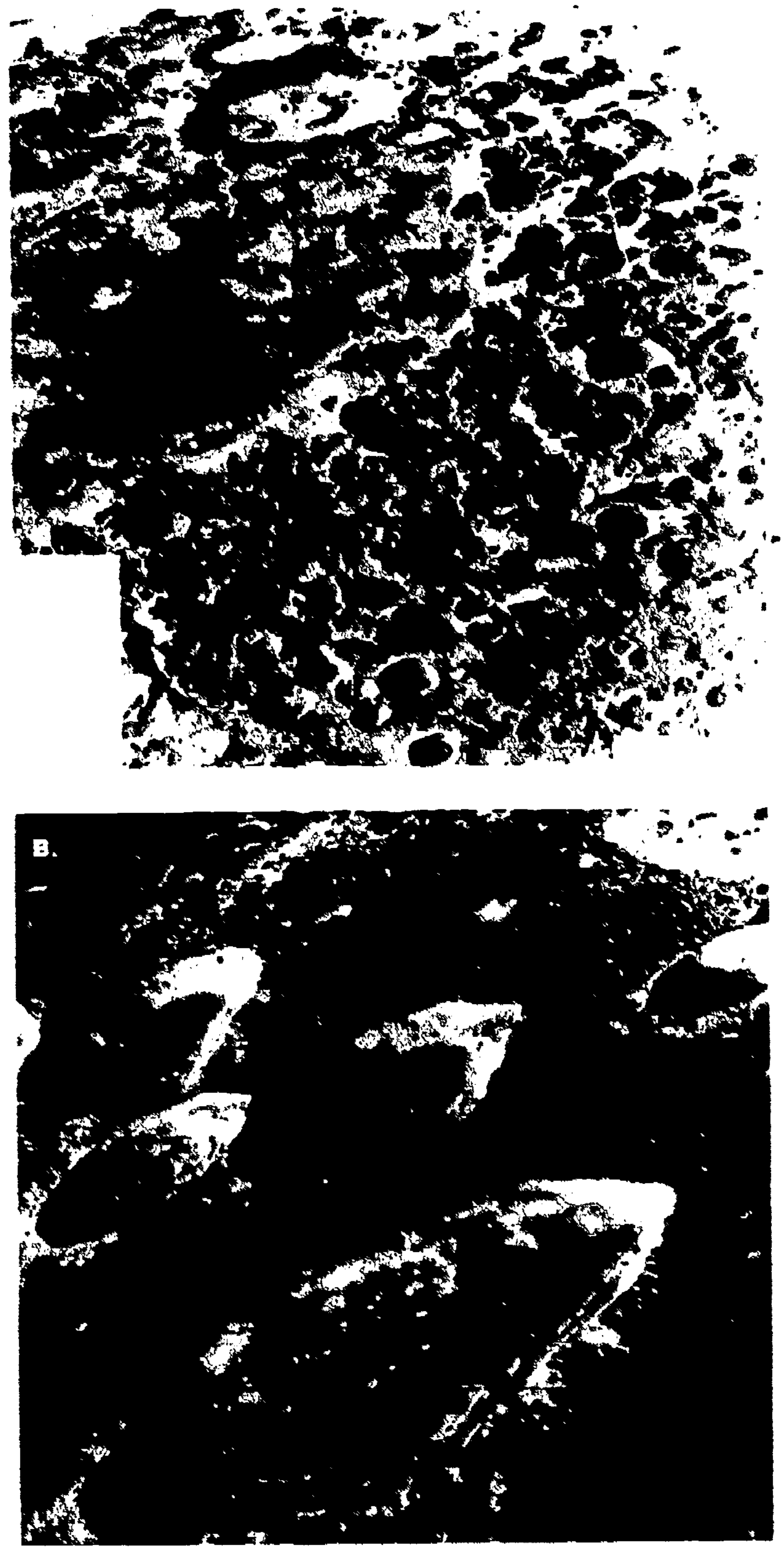
The martian atmosphere, like that of Venus, is primarily carbon dioxide. Nitrogen and oxygen are present only in small percentages. Martian air contains only about 1/1,000



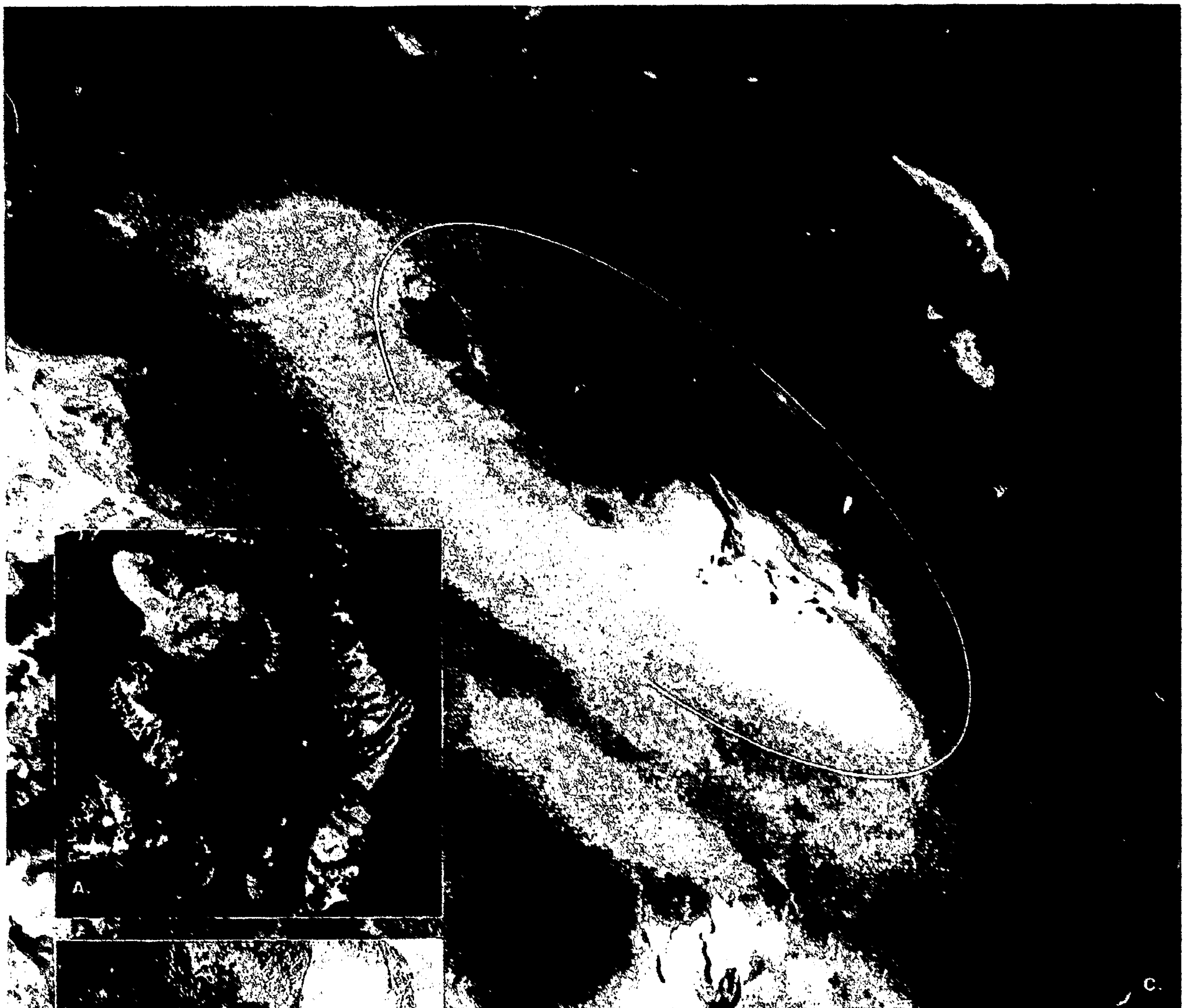
Light patches of water-ice frost on Utopia Planitia, Viking Lander 2's landing site, were observed by the spacecraft during the martian winter.

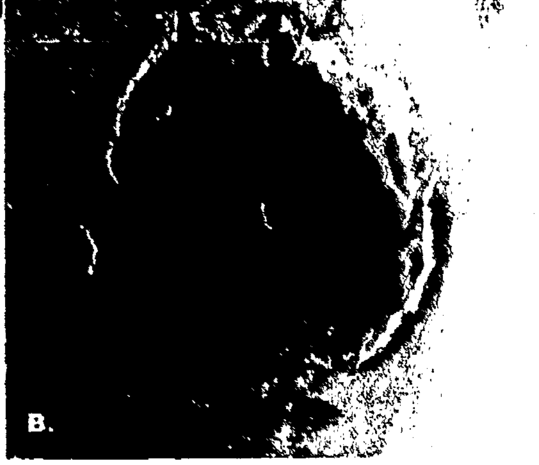


These martian channels (A) wind their way northwest (upper left) for several hundred kilometers. The origin of the channels is controversial: Did they form from lava flows or from water released by the melting of ground ice during volcanic eruptions? The martian channels resemble these dry channels (B) in the coastal desert of Peru.



Impact craters are formed when a planetary surface is struck by a meteorite. Mercury, our Moon and many of the icy, rocky satellites of the outer solar system are characterized by heavily cratered surfaces. Earth's geological processes tend to destroy evidence of ancient crater impacts, although some more recent craters remain discernible. Compare martian craters (A) with those on the Moon (B).





Volcanoes are vents in a planet's or moon's crust permitting the escape of internal heat. Earth has hundreds of active volcanoes, like those on the island of Hawaii (A). Hawaiian volcanoes are very similar in shape to Mars' extinct Olympus Mons (B), which is three times the height of Mount Everest and has a base that would cover the state of Nevada. The most volcanically active body in the solar system is Jupiter's moon Io (C). In this photographic mosaic of the moon, a cloud of ejecta, or ejected material (top), is visible 280 kilometers (175 miles) above the surface, hurled there by the violent volcano Pele (highlighted).

Rocks litter the rolling martian landscape seen by Viking Lander 1. The large boulder (left), named Big Joe, measures 1 by 3 meters (3 by 10 feet) and is 8 meters (26 feet) from the spacecraft. The vertical white object (near center) is part of the spacecraft's meteorological boom.

as much water as our air, but even this small amount can condense out, forming clouds that ride high in the atmosphere or swirl around the slopes of towering volcanoes. Local patches of early morning fog can form in valleys.

There is evidence that in the past a denser martian atmosphere may have allowed water to flow on the planet. Physical features closely resembling shorelines, gorges, riverbeds and islands suggest that great rivers once marked the planet.

Mars has two moons, Phobos and Deimos. They are small and irregularly shaped and possess ancient, cratered surfaces. It is possible the moons were originally asteroids that ventured too close to Mars and were captured by its gravity.

The Viking Orbiters and Landers exceeded by large margins their design lifetimes of 120 and 90 days, respectively. The first to fail was Viking Orbiter 2, which stopped operating on July 24, 1978, when a leak depleted its attitude-control gas. Viking Lander 2 operated until April 12, 1980, when it was shut down due to battery degeneration. Viking Orbiter 1 quit on August 7, 1980, when the last of its attitude-control gas was used up. Viking Lander 1 ceased functioning on November 13, 1983.

Despite the inconclusive results of the Viking biology experiments, we know more about Mars than any other planet except Earth. NASA's Mars Observer spacecraft, to be launched in September 1992, will expand our knowledge of the martian environment and lead to human exploration of the red planet.

Mars' Valles Marineris (Mariner Valley) would stretch from the Pacific to the Atlantic Oceans, swallowing up the Grand Canyon. Appearing like a long scar across the face of Mars, the valley was formed when lava from volcanoes drained out of a reservoir below the surface and the crust collapsed.

Phobos, the larger of Mars' two tiny moons, is the first asteroid-like object seen up close. It might be a typical asteroid that was trapped by Mars' gravity.

Asteroids

The solar system has a large number of rocky and metallic objects that are in orbit around the Sun but are too small to be considered full-fledged planets. These objects are known as asteroids or minor planets. Most, but not all, are found in a band or belt between the orbits of Mars and Jupiter. Some have orbits that cross Earth's path, and there is evidence that Earth has been hit by asteroids in the past. One of the least eroded, best preserved examples is the Barringer Meteor Crater near Winslow, Arizona.

Asteroids are material left over from the formation of the solar system. One theory suggests that they are the remains of a planet that was destroyed in a massive collision long ago. More likely, asteroids are material that never coalesced into a planet. In fact, if the estimated total mass of all asteroids was gathered into a single object, the object would be only about 1,500 kilometers (932 miles) across — less than half the diameter of our Moon.

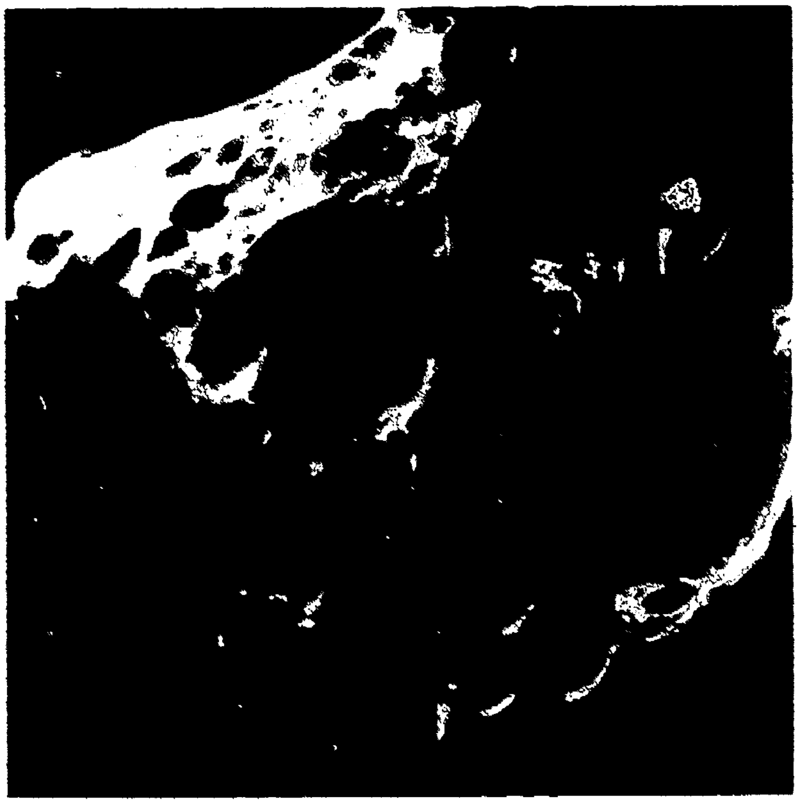
Thousands of asteroids have been identified from Earth. It is estimated that 100,000 are bright enough to eventually be photographed through Earth-based telescopes.

Much of our understanding about asteroids comes from examining pieces of space debris that fall to the surface of Earth. Asteroids that are on a collision course with Earth are called *meteoroids*. When a meteoroid strikes our atmosphere at high velocity, friction causes this chunk of space matter to incinerate in a streak of light known as a *meteor*. If the meteoroid does not burn up completely, what's left strikes Earth's surface and is called a *meteorite*. One of the best places to look for meteorites is the ice cap of Antarctica.

Of all the meteorites examined, 92.8 percent are composed of silicate (stone), and 5.7 percent are composed of iron and nickel; the rest are a mixture of the three materials. Stony meteorites are the hardest to identify since they look very much like terrestrial rocks.

Since asteroids are material from the very early solar system, scientists are interested in their composition. Spacecraft that have flown through the asteroid belt have found that the belt is really quite empty and that asteroids are separated by very large distances.

Current and future missions will fly by selected asteroids for closer examination. The Galileo Orbiter, launched by NASA in October 1989, will investigate main-belt asteroids on its way to Jupiter. The Comet Rendezvous/Asteroid Flyby (CRAF) and Cassini missions will also study these far-flung objects. Scheduled for launch in the latter part of the 1990s, the CRAF and Cassini missions are a collaborative project of NASA, the European Space Agency and the federal space agencies of Germany and Italy, as well as the United States Air Force and the Department of Energy. One day, space factories will mine the asteroids for raw materials.



A spacecraft–asteroid rendezvous is shown in this artist's conception of a possible future mission.

Jupiter

Beyond Mars and the asteroid belt, in the outer regions of our solar system, lie the giant planets of Jupiter, Saturn, Uranus and Neptune. In 1972, NASA dispatched the first of four spacecraft slated to conduct the initial surveys of these colossal worlds of gas and their moons of ice and rock. Jupiter was the first port of call.

Pioneer 10, which lifted off from Kennedy Space Center in March 1972, was the first spacecraft to penetrate the asteroid belt and travel to the outer regions of the solar system. In December 1973, it returned the first close-up images of Jupiter, flying within 132,252 kilometers (82,178 miles) of the planet's banded cloud tops. Pioneer 11 followed a year later. Voyagers 1 and 2 were launched in the summer of 1977 and returned spectacular photographs of Jupiter and its family of satellites during flybys in 1979.

These travelers found Jupiter to be a whirling ball of liquid hydrogen and helium, topped with a colorful atmosphere composed mostly of gaseous hydrogen and helium. Ammonia ice crystals form white Jovian clouds. Sulfur compounds (and perhaps phosphorus) may produce the brown and orange hues that characterize Jupiter's atmosphere.

It is likely that methane, ammonia, water and other gases react to form organic molecules in the regions between the planet's frigid cloud tops and the warmer hydrogen ocean lying below. Because of Jupiter's atmospheric dynamics, however, these organic compounds — if they exist — are probably short-lived.

The Great Red Spot has been observed for centuries through telescopes on Earth. This hurricane-like storm in Jupiter's atmosphere is more than twice the size of our planet. As a high-pressure region, the Great Red Spot spins in a direction opposite to that of low-pressure storms on Jupiter; it is surrounded by swirling currents that rotate around the spot and are sometimes consumed by it. The Great Red Spot might be a million years old.

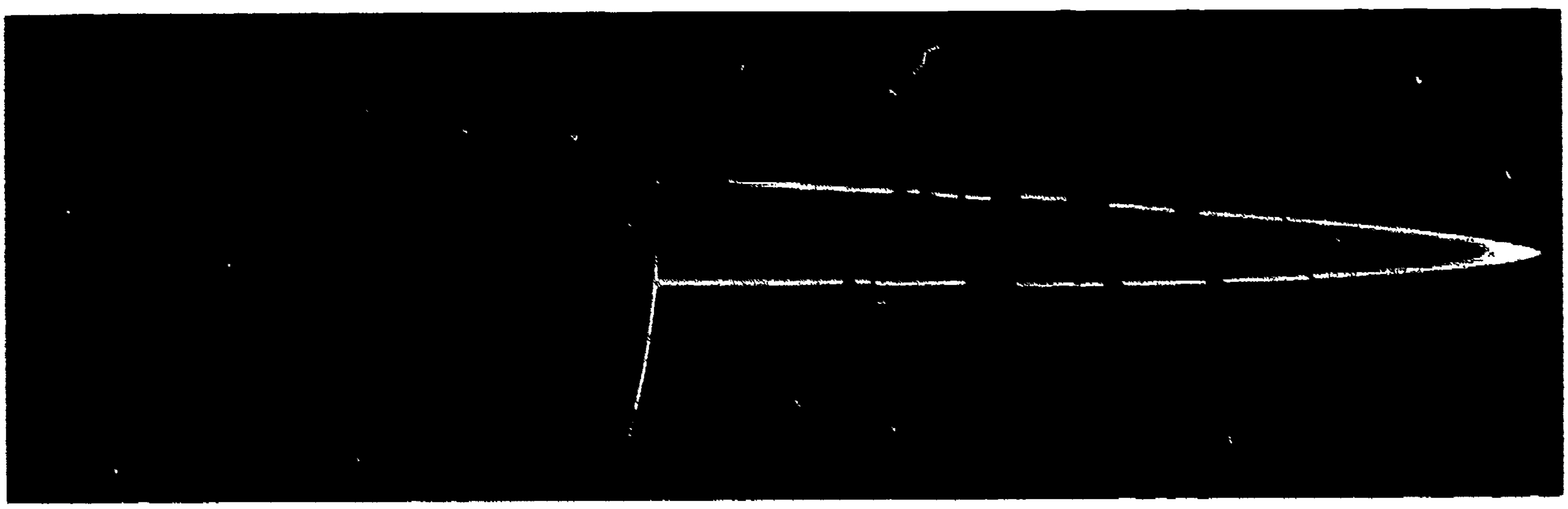
Our spacecraft detected lightning in Jupiter's upper atmosphere and observed auroral emissions similar to Earth's northern lights at the Jovian polar regions. Voyager 1 returned the first images of a faint, narrow ring encircling Jupiter.

Largest of the solar system's planets, Jupiter rotates at a dizzying pace — once every 9 hours 55 minutes 30 seconds. The massive planet takes almost 12 Earth years to complete a journey around the Sun. With 16 known moons, Jupiter is something of a miniature solar system.

A new mission to Jupiter — the Galileo Project — is under way. After a six-year cruise that takes the Galileo Orbiter once past Venus, twice past Earth and the Moon and once past two asteroids, the spacecraft will drop an atmospheric probe into Jupiter's cloud layers and relay data back to Earth. The Galileo Orbiter will spend two years circling the planet and flying close to Jupiter's large moons, exploring in detail what the two Pioneers and two Voyagers revealed.

Jupiter fills the sky for the Voyager 1 spacecraft and the moons Io (left) and Europa. Io is passing over the Great Red Spot.

The Jovian atmosphere, with its spectacular collection of cloud bands, spots and waves, is constantly in motion. The moons Io (left) and Europa can be seen in this image from Voyager 1.



Jupiter's very thin ring is seen by Voyager 2. This mosaic of images was taken while the spacecraft was in the planet's shadow.

Galilean Satellites

In 1610, Galileo Galilei aimed his telescope at Jupiter and spotted four points of light orbiting the planet. For the first time, humans had seen the moons of another world. In honor of their discoverer, these four bodies would become known as the Galilean satellites or moons. But Galileo might have happily traded this honor for one look at the dazzling photographs returned by the Voyager spacecraft as they flew past these planet-sized satellites.

One of the most remarkable findings of the Voyager mission was the presence of active volcanoes on the Galilean moon Io. Volcanic eruptions had never before been observed on a world other than Earth. The Voyager cameras identified at least nine active volcanoes on Io, with plumes of ejected material extending as far as 280 kilometers (175 miles) above the moon's surface.

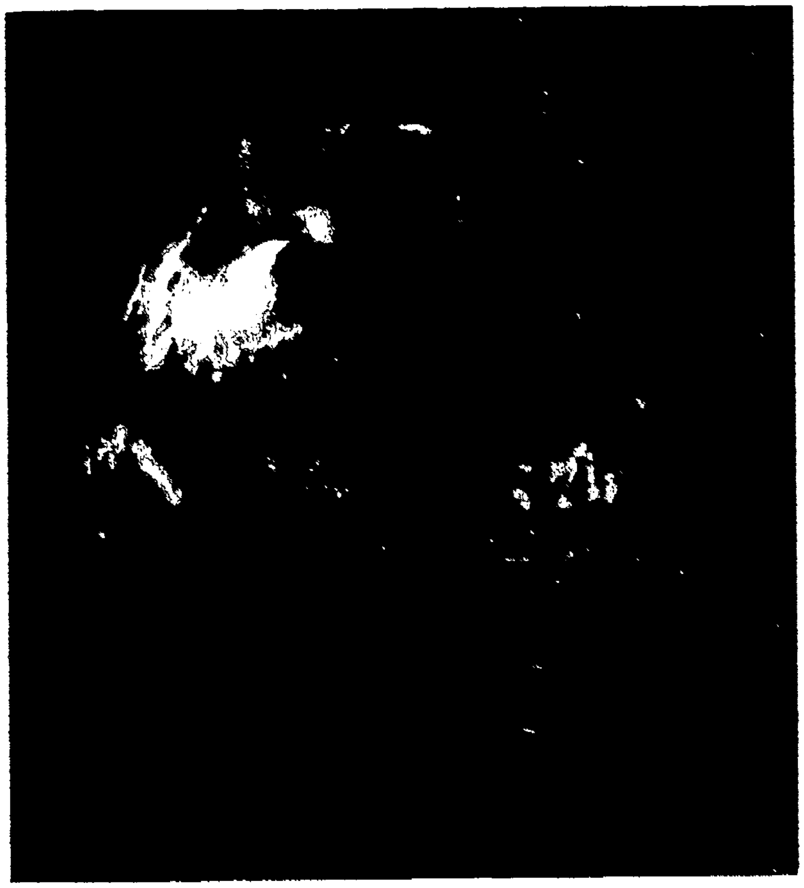
Io's pizza-colored terrain, marked by orange and yellow hues, is probably the result of sulfur-rich materials brought to the surface by volcanic activity. Volcanic activity on this satellite is the result of tidal flexing caused by the gravitational tug-of-war between Io, Jupiter and the other three Galilean moons.

Europa, approximately the same size as our Moon, is the brightest Galilean satellite. The moon's surface displays a complex array of streaks, indicating the crust has been fractured. Caught in a gravitational tug-of-war like Io, Europa has been heated enough to cause its interior ice to melt — apparently producing a liquid-water ocean. This ocean is covered by an ice crust that has formed where water is exposed to the cold of space. Europa's core is made of rock that sank to its center.

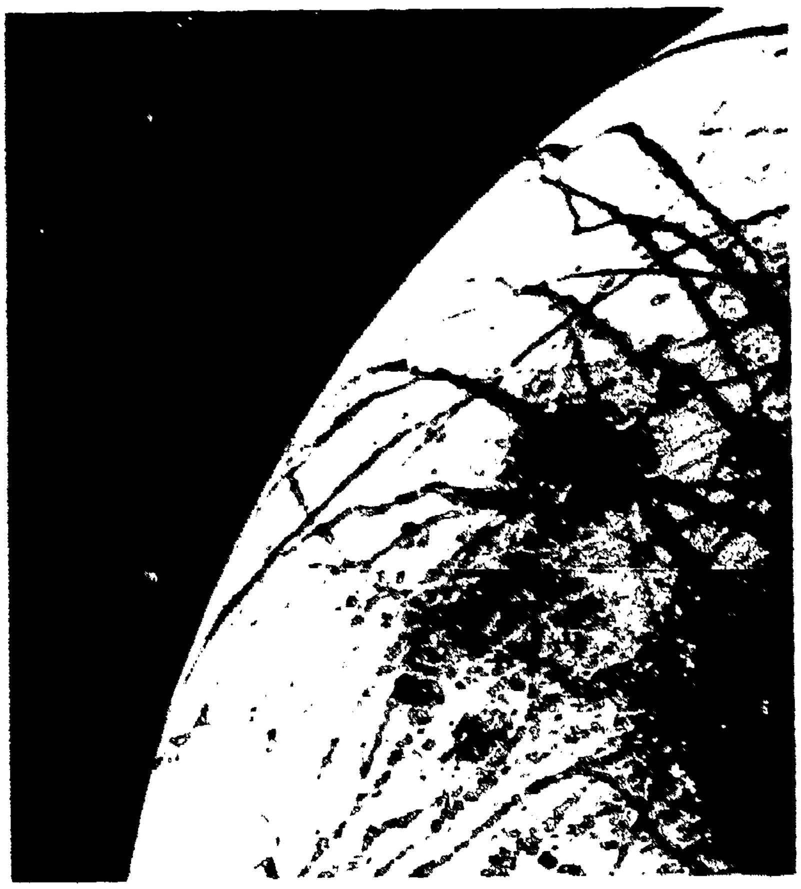
Like Europa, the other two Galilean moons — Ganymede and Callisto — are worlds of ice and rock. Ganymede is the largest satellite in the solar system — larger than the planets Mercury and Pluto. The satellite is composed of about 50 percent water or ice and the rest rock. Ganymede's surface has areas of different brightness, indicating that, in the past, material oozed out of the moon's interior and was deposited at various locations on the surface.

Callisto, only slightly smaller than Ganymede, has the lowest density of any Galilean satellite, suggesting that large amounts of water are part of its composition. Callisto is the most heavily cratered object in the solar system; no activity during its history has erased old craters except more impacts.

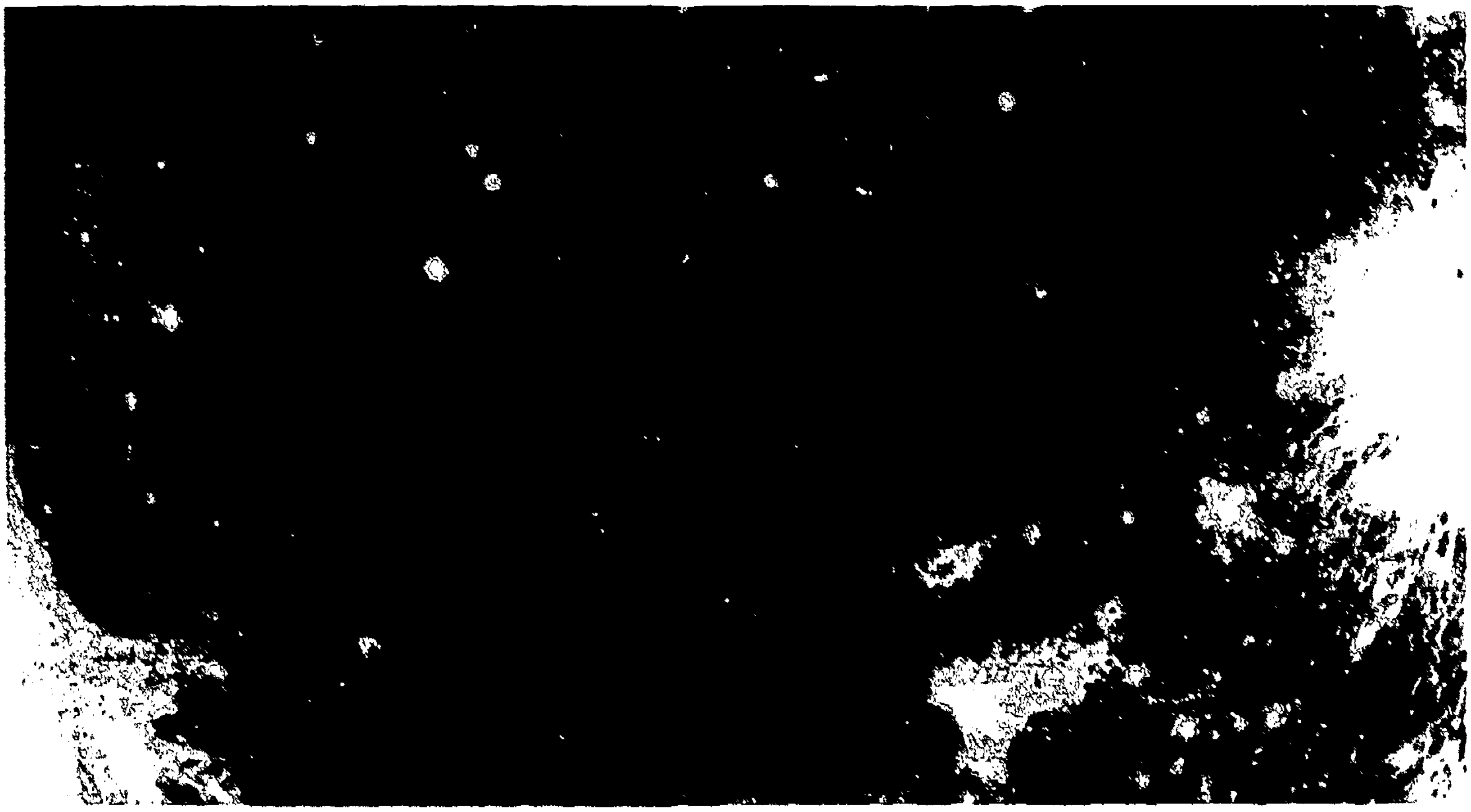
Detailed studies of all the Galilean satellites will be performed by the Galileo Orbiter.

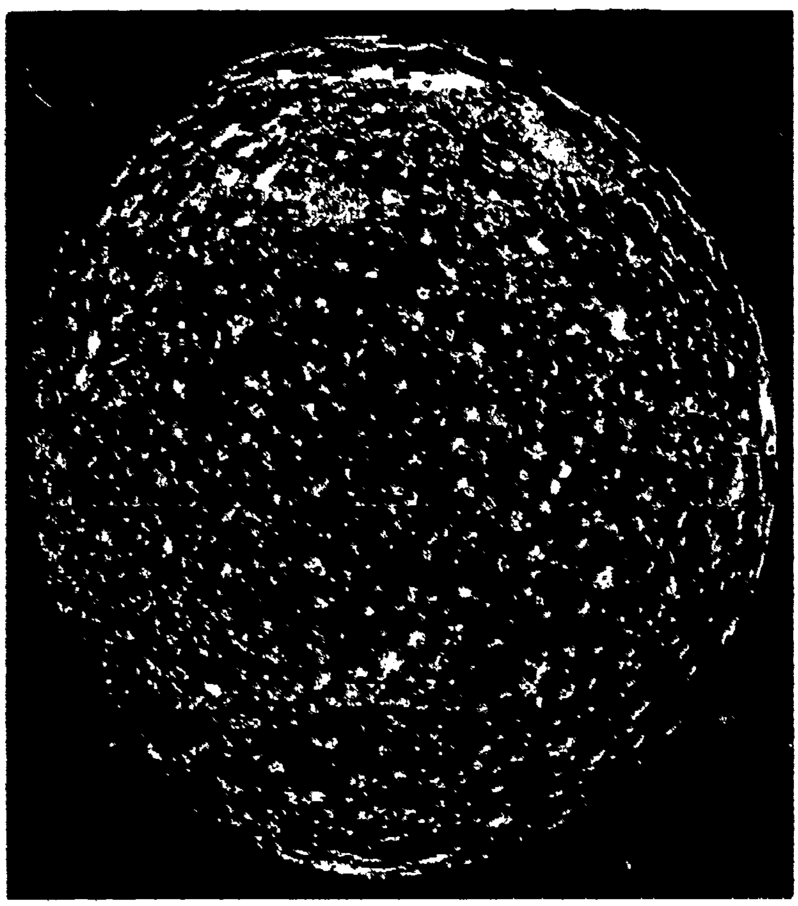


Active and dormant volcanoes dot Io's landscape. The light ring (center) is formed by material erupting from the volcano Prometheus; the ejecta cloud (left) is from Pele.



Europa's dark lines are cracks in its surface, a floating ice sheet. Europa is the smoothest moon in the solar system.





Ganymede's lighter areas have been active more recently than the darker regions. The small, bright spots are the result of impacts exposing fresh, clean ice.

No spot on Callisto's surface has escaped bombardment, as shown in this enhanced view (left).

Saturn

No planet in the solar system is adorned like Saturn. Its exquisite ring system is unrivaled. Like Jupiter, Saturn is composed mostly of hydrogen. But in contrast to the vivid colors and wild turbulence found in Jovian clouds, Saturn's atmosphere has a more subtle, butterscotch hue, and its markings are muted by high-altitude haze. Given Saturn's somewhat placid-looking appearance, scientists were surprised at the high-velocity equatorial jet stream that blows some 1,770 kilometers (1,100 miles) per hour.

Three American spacecraft have visited Saturn. Pioneer 11 sped by the planet and its moon Titan in September 1979, returning the first close-up images. Voyager 1 followed in November 1980, sending back breathtaking photographs that revealed for the first time the complexities of Saturn's ring system and moons. Voyager 2 flew by the planet and its moons in August 1981.

The rings are composed of countless low-density particles orbiting individually around Saturn's equator at progressive distances from the cloud tops. Analysis of spacecraft radio waves passing through the rings showed that the particles vary widely in size, ranging from dust to house-sized boulders. The rings are bright because they are mostly ice and frosted rock.

The rings might have resulted when a moon or a passing body ventured too close to Saturn. The unlucky object would have been torn apart by great tidal forces on its surface and in its interior. Or the object may not have been fully formed to begin with and disintegrated under the influence of Saturn's gravity. A third possibility is that the object was shattered by collisions with larger objects orbiting the planet.

Unable either to form into a moon or to drift away from each other, individual ring particles appear to be held in place by the gravitational pull of Saturn and its satellites. These complex gravitational interactions form the thousands of ringlets that make up the major rings.

Radio emissions quite similar to the static heard on an AM car radio during an electrical storm were detected by the Voyager spacecraft. These emissions are typical of lightning but are believed to be coming from Saturn's ring system rather than its atmosphere, where no lightning was observed. As they had at Jupiter, the Voyagers saw a version of Earth's auroras near Saturn's poles.

The Voyagers discovered new moons and found several satellites that share the same orbit. We learned that some moons shepherd ring particles, maintaining Saturn's rings and the gaps in the rings. Saturn's 18th moon was discovered in 1990 from images taken by Voyager 2 in 1981.

Voyager 1 determined that Titan has a nitrogen-based atmosphere with methane and argon — one more like Earth's in composition than the carbon dioxide atmospheres of Mars and Venus. Titan's surface temperature of –179 degrees Celsius (–290 degrees Fahrenheit) implies

Shadowy "spokes" appear to be very fine particles lifted slightly out of the plane of the rings by Saturn's magnetic field.

High, thin layers of haze rise above Titan's main cloud deck. The highest layer is about 700 kilometers (435 miles) above the moon's surface.

Saturn's cloud bands, rings and some of its 18 moons (above) are visible to the approaching Voyager 2. Gaps in the rings can be seen.

Saturn's rings vary in brightness; these variations correspond to the size and thickness of the ring particles. The dark grey region (right) and the thinner grey band running from the upper left to the lower right (known as the Cassini Division) have only a thin layer of dust-size particles.

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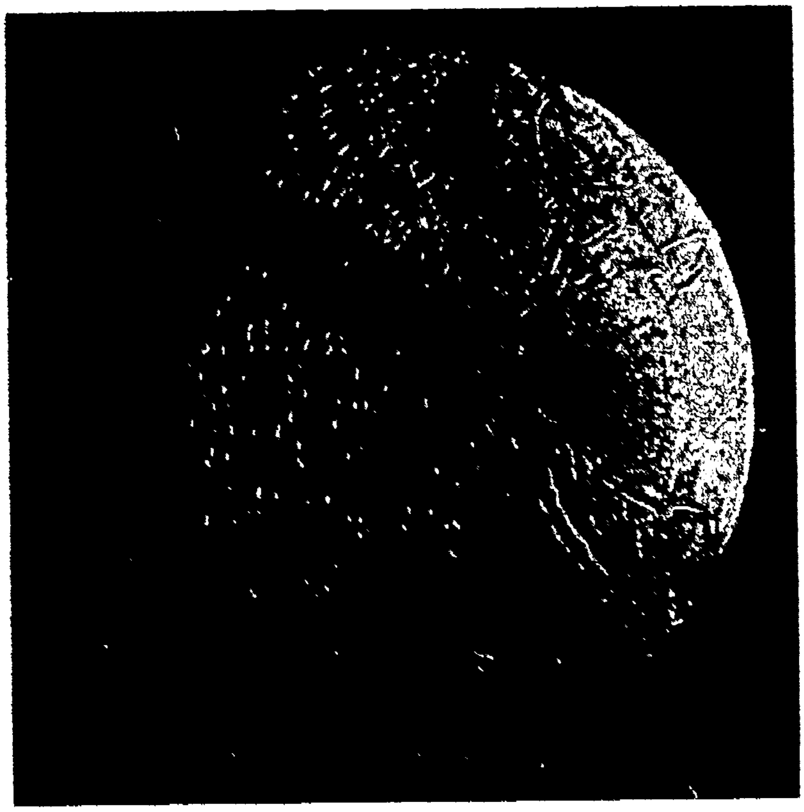


An ice ball about 500 kilometers (310 miles) in diameter, Saturn's moon Enceladus has had episodes in which sections of it have been resurfaced.

that there might be water-ice islands rising above oceans of ethane–methane liquid or sludge. Unfortunately, Voyager 1's cameras could not penetrate the moon's dense clouds.

Continuing photochemistry from solar radiation may be converting Titan's methane to ethane, acetylene and — in combination with nitrogen — hydrogen cyanide. The latter compound is a building block of amino acids. These conditions may be similar to the atmospheric conditions of primeval Earth between three and four billion years ago. However, Titan's atmospheric temperature is believed to be too low to permit progress beyond this stage of organic chemistry.

The exploration of Saturn will continue with the Cassini mission. The Cassini spacecraft will orbit the planet and will also deploy a probe called Huygens, which will be dropped into Titan's atmosphere and fall to the surface. Cassini will use the probe as well as radar to peer through Titan's clouds and will spend years examining the Saturnian system.

Uranus

In January 1986, four and a half years after visiting Saturn, Voyager 2 completed the first close-up survey of the Uranian system. The brief flyby revealed more information about Uranus and its retinue of icy moons than had been gleaned from ground observations since the planet's discovery over two centuries ago by the English astronomer William Herschel.

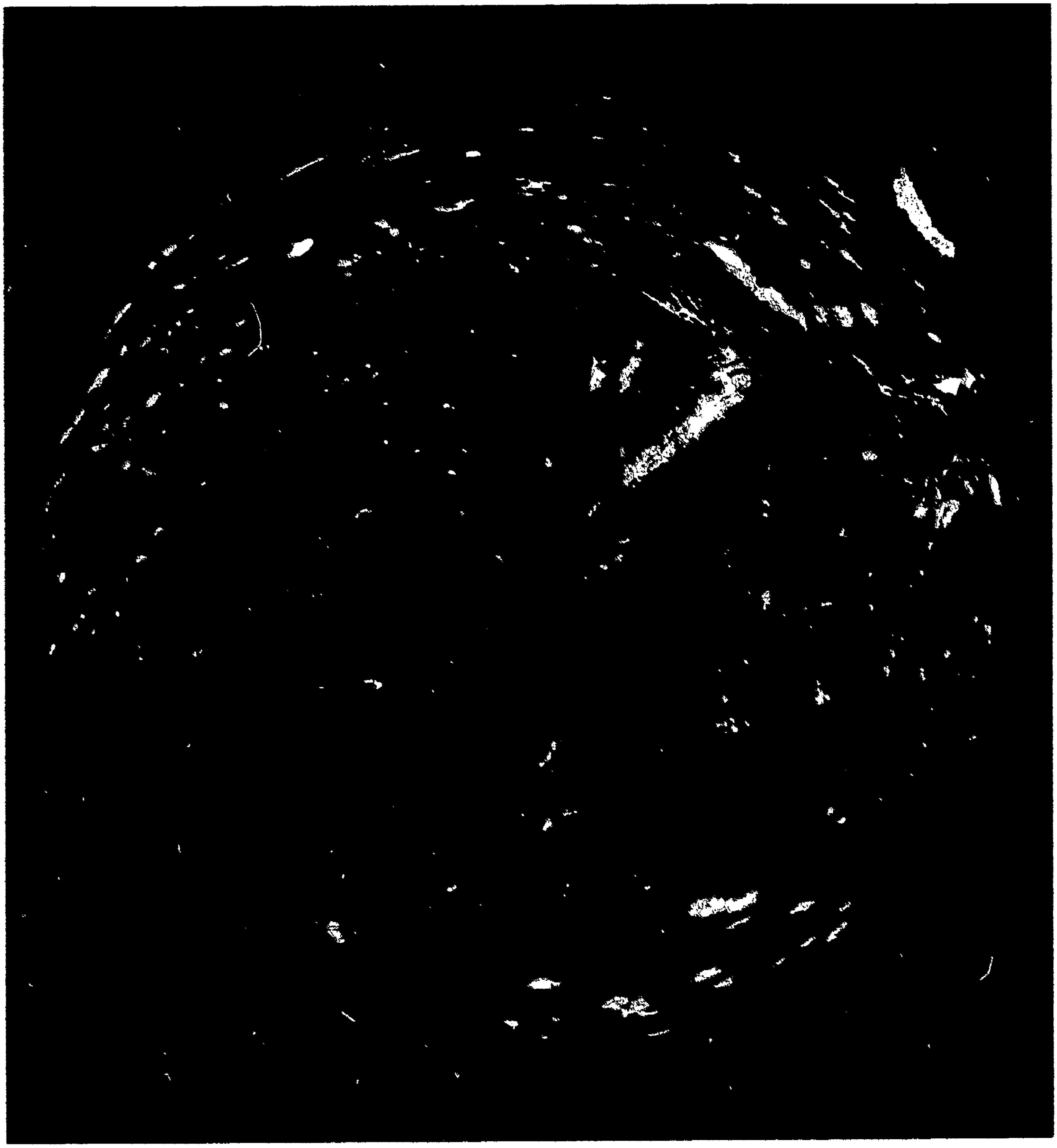
Uranus, third largest of the planets, is an oddball of the solar system. Unlike the other planets (with the exception of Pluto), this giant lies tipped on its side with its north and south poles alternately facing the Sun during an 84-year swing around the solar system. During Voyager 2's flyby, the south pole faced the Sun. Uranus might have been knocked over when an Earth-sized object collided with it early in the life of the solar system.

Voyager 2 discovered that Uranus' magnetic field does not follow the usual north–south axis found on the other planets. Instead, the field is tilted 60 degrees and offset from the planet's center, a phenomenon that on Earth would be like having one magnetic pole in New York City and the other in the city of Djakarta, on the island of Java in Indonesia.

Uranus' atmosphere consists mainly of hydrogen, with some 12 percent helium and small amounts of ammonia, methane and water vapor. The planet's blue color occurs because methane in its atmosphere absorbs all other colors. Wind speeds range up to 580 kilometers (360 miles) per hour, and temperatures near the cloud tops average –221 degrees Celsius (–366 degrees Fahrenheit).

Uranus' sunlit south pole is shrouded in a kind of photochemical "smog" believed to be a combination of acetylene, ethane and other sunlight-generated chemicals. Surrounding the planet's atmosphere and extending thousands of kilometers into space is a mysterious ultraviolet sheen known as "electroglow."

Uranus' clouds are virtually featureless, unlike those of the other giant, gaseous planets in the outer solar system. Both pictures are from Voyager 2. The left image is unenhanced; the right enhances contrasts to highlight zonal bands in the atmosphere. The occasional, small doughnut shapes are out-of-focus dust particles on the camera lens.



Miranda is characterized by sharp variations in terrain. The ice cliffs (upper right) are 20 kilometers (12 miles) high.

Uranus' rings, which appear dark from Earth, are brightened by sunlight passing through them in this photograph taken by Voyager 2. Parts of the rings are smeared and stars register as streaks in this long exposure.

Approximately 8,000 kilometers (5,000 miles) below Uranus' cloud tops, there is thought to be a scalding ocean of water and dissolved ammonia some 10,000 kilometers (6,200 miles) deep. Beneath this ocean is an Earth-sized core of heavier materials.

Voyager 2 discovered 10 new moons, 16–169 kilometers (10–105 miles) in diameter, orbiting Uranus. The five previously known — Miranda, Ariel, Umbriel, Titania and Oberon — range in size from 520 to 1,610 kilometers (323 to 1,000 miles) across. Representing a geological showcase, these five moons are half-ice, half-rock spheres that are cold and dark and show evidence of past activity, including faulting and ice flows.

The most remarkable of Uranus' moons is Miranda. Its surface features high cliffs as well as canyons, crater-pocked plains and winding valleys. The sharp variations in terrain suggest that, after the moon formed, it was smashed apart by a collision with another body — an event not unusual in our solar system, which contains many objects that have impact craters or are fragments from large impacts. What is extraordinary is that Miranda apparently reformed with some of the material that had been in its interior exposed on its surface.

Uranus was thought to have nine dark rings; Voyager 2 imaged 11. In contrast to Saturn's rings, which are composed of bright particles, Uranus' rings are primarily made up of dark, boulder-sized chunks.

Neptune

Voyager 2 completed its 12-year tour of the solar system with an investigation of Neptune and the planet's moons. On August 25, 1989, the spacecraft swept to within 4,850 kilometers (3,010 miles) of Neptune and then flew on to the moon Triton. During the Neptune encounter, it became clear that the planet's atmosphere was more active than Uranus'.

Voyager 2 observed the Great Dark Spot, a circular storm the size of Earth, in Neptune's atmosphere. Resembling Jupiter's Great Red Spot, the storm spins counterclockwise and moves westward at almost 1,200 kilometers (745 miles) per hour. Voyager 2 also noted a smaller dark spot and a fast-moving cloud dubbed the "Scooter," as well as high-altitude clouds over the main hydrogen and helium cloud deck. The highest wind speeds of any planet were observed, up to 2,400 kilometers (1,500 miles) per hour.

Like the other giant planets, Neptune has a gaseous hydrogen and helium upper layer over a liquid interior. The planet's core contains a higher percentage of rock and metal than those of the other gas giants. Neptune's distinctive blue appearance, like Uranus' blue color, is due to atmospheric methane.

Neptune's magnetic field is tilted relative to the planet's spin axis and is not centered at the core. This phenomenon is similar to Uranus' magnetic field and suggests that the fields of the two giants are being generated in an area above the cores, where the pressure is so great that liquid hydrogen assumes the electrical properties of a metal. Earth's magnetic field, on the other hand, is produced by its spinning metallic core and is only slightly tilted and offset relative to its center.

Voyager 2 also shed light on the mystery of Neptune's rings. Observations from Earth indicated that there were arcs of material in orbit around the giant planet. It was not clear how Neptune could have arcs and how these could be kept from spreading out into even, unclumped rings. Voyager 2 detected these arcs, but they were, in fact, part of thin, complete rings. A number of small moons could explain the arcs, but such bodies were not spotted.

Astronomers had identified the Neptunian moons Triton in 1846 and Nereid in 1949. Voyager 2 found six more. One of the new moons — Proteus — is actually larger than Nereid, but since Proteus orbits close to Neptune, it was lost in the planet's glare for observers on Earth.

Triton circles Neptune in a retrograde orbit in under six days. Tidal forces on Triton are causing it to spiral slowly towards the planet. In 10 to 100 million years (a short time in astronomical terms), the moon will be so close that Neptunian gravity will tear it apart, forming a spectacular ring to accompany the planet's modest current rings.

Triton's landscape is as strange and unexpected as those of Io and Miranda. The moon has more rock than its

counterparts at Saturn and Uranus. Triton's mantle is probably composed of water-ice, but its crust is a thin veneer of nitrogen and methane. The moon shows two dramatically different types of terrain: the so-called "cantaloupe" terrain and a receding ice cap.

Dark streaks appear on the ice cap. These streaks are the fallout from geyser-like volcanic vents that shoot nitrogen gas and dark, fine-grained particles to heights of 2–8 kilometers (1–5 miles). Triton's thin atmosphere, only 1/70,000th as thick as Earth's, has winds that carry the dark particles and deposit them as streaks on the ice cap — the coldest surface yet discovered in the solar system (–235 degrees Celsius, –391 degrees Fahrenheit). Triton might be more like Pluto than any other object spacecraft have so far visited.

The Great Dark Spot (top), the cloud named "Scooter" (middle) and Dark Spot 2 (bottom) with its bright core are the most prominent features in Neptune's atmosphere.

This photograph overexposed Neptune (appearing as a crescent) to highlight the three clumps in the planet's outer ring.

Most of Triton's features are unique in the solar system. The orientation of the dark streaks (bottom) shows that winds were blowing from the lower left towards the upper right when Voyager 2 flew by.

Pluto

A possible future mission to Pluto (right) and its moon Charon is shown in this artist's rendering.

Pluto is the most distant of the planets, yet the eccentricity of its orbit periodically carries it inside Neptune's orbit, where it has been since 1979 and where it will remain until March 1999. Pluto's orbit is also highly inclined — tilted 17 degrees to the orbital plane of the other planets.

Discovered in 1930, Pluto appears to be little more than a celestial snowball. The planet's diameter is calculated to be approximately 2,300 kilometers (1,430 miles), only two-thirds the size of our Moon. Ground-based observations indicate that Pluto's surface is covered with methane ice and that there is a thin atmosphere that may freeze and fall to the surface as the planet moves away from the Sun. Observations also show that Pluto's spin axis is tipped by 122 degrees.

The planet has one known satellite, Charon, discovered in 1978. Charon's surface composition is different from Pluto's: the moon appears to be covered with water-ice rather than methane ice. Its orbit is gravitationally locked with Pluto, so both bodies always keep the same hemisphere facing each other. Pluto's and Charon's rotational period and Charon's period of revolution are all 6.4 Earth days.

Although no spacecraft have ever visited Pluto, NASA is currently exploring the possibility of such a mission.

Comets

The outermost members of the solar system occasionally pay a visit to the inner planets. As asteroids are the rocky and metallic remnants of the formation of the solar system, comets are the icy debris from that dim beginning and can survive only far from the Sun. Most comet nuclei reside in the Oort Cloud, a loose swarm of objects in a halo beyond the planets and reaching perhaps halfway to the nearest star.

Comet nuclei orbit in this frozen abyss until they are gravitationally perturbed into new orbits that carry them close to the Sun. As a nucleus falls inside the orbits of the outer planets, the volatile elements of which it is made gradually warm; by the time the nucleus enters the region of the inner planets, these volatile elements are boiling. The nucleus itself is irregular and only a few miles across, and is made principally of water-ice with methane and ammonia — materials very similar to those composing the moons of the giant planets.

As these materials boil off of the nucleus, they form a *coma* or cloud-like "head" that can measure tens of thousands of kilometers across. The coma grows as the comet gets closer to the Sun. The stream of charged particles coming from the Sun pushes on this cloud, blowing it back like a flag in the wind and giving rise to the comet's "tails." Gases and ions are blown directly back from the nucleus, but dust particles are pushed more slowly. As the nucleus continues in its orbit, the dust particles are left behind in a curved arc.

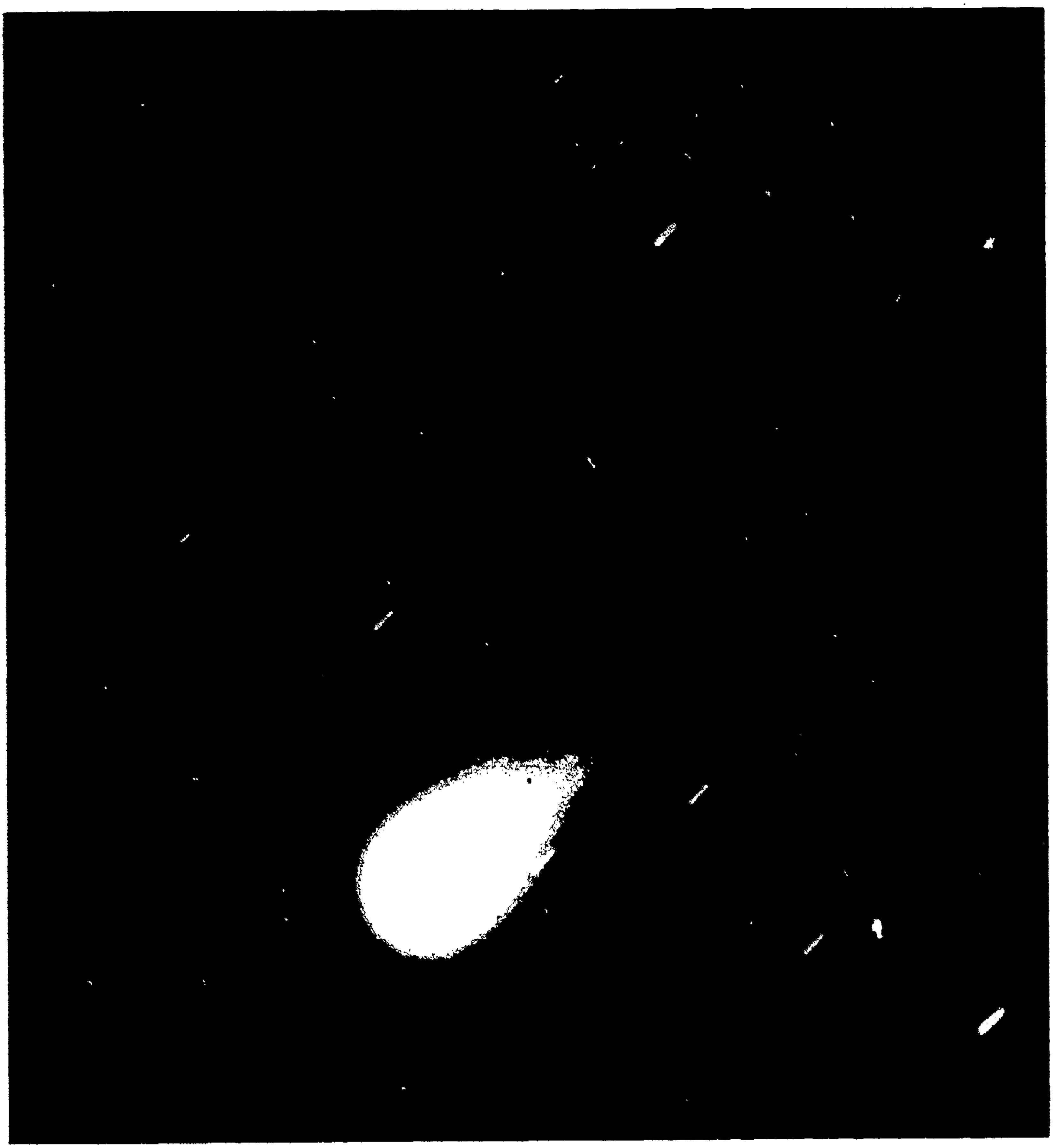
Both the gas and dust tails point away from the Sun; in effect, the comet chases its tails as it recedes from the Sun. The tails can reach 150 million kilometers (93 million miles) in length, but the total amount of material contained in this dramatic display would fit in an ordinary suitcase. Comets — from the Latin *cometa*, meaning "long-haired" — are essentially dramatic light shows.

Some comets pass through the solar system only once, but others have their orbits gravitationally modified by a close encounter with one of the giant outer planets. These latter visitors can enter closed elliptical orbits and repeatedly return to the inner solar system.

Halley's Comet is the most famous example of a relatively short period comet, returning on an average of once every 76 years and orbiting from beyond Neptune to within Venus' orbit. Confirmed sightings of the comet go back to 240 B.C. This regular visitor to our solar system is named for Sir Edmund Halley, because he plotted the comet's orbit and predicted its return, based on earlier sightings and Newtonian laws of motion. His name became part of astronomical lore when, in 1759, the comet returned on schedule. Unfortunately, Sir Edmund did not live to see it.

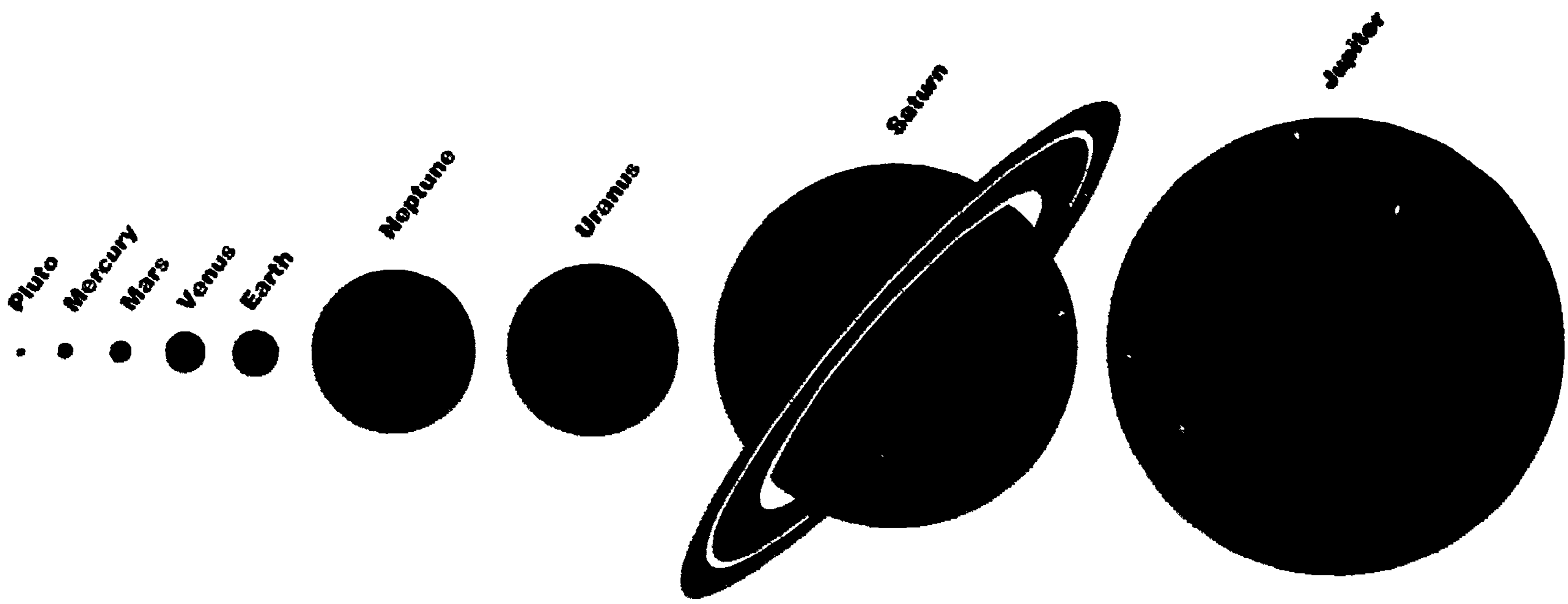
A comet can be very prominent in the sky if it passes comparatively close to Earth. Unfortunately, on its most recent appearance, Halley's Comet passed no closer than 62.4 million kilometers (38.8 million miles) from our world. The comet was visible to the naked eye, especially for viewers in the southern hemisphere, but it was not spectacular. Comets have been so bright, on rare occasions, that they were visible during daytime. Historically, comet sightings have been interpreted as bad omens and have been artistically rendered as daggers in the sky.

The Comet Rendezvous/Asteroid Flyby (CRAF) spacecraft will become the first traveler to fly close to a comet nucleus and remain in proximity to it as they both approach the Sun. CRAF will observe the nucleus as it becomes active in the growing sunlight and begins to have its lighter elements boil off and form a coma and tails. Several spacecraft have flown by comets at high speed; the first was NASA's International Cometary Explorer in 1985. An armada of five spacecraft (two Japanese, two Soviet and the Giotto spacecraft from the European Space Agency) flew by Halley's Comet in 1986.



Halley's Comet, the most famous of all comets, last visited the inner solar system in 1986. It will return again in 2061.

The Planets at a Glance



	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Mean Distance From Sun									
Millions of Kilometers	57 9	108 2	149 6	227.9	778 3	1,429	2 8/5	4,504	5.900
Millions of Miles	36	67 2	93	141.6	483.6	888 2	1,786	2,799	3,666
Period of Revolution*	87.97 days	224.7 days	365.26 days	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Period of Rotation*	58 65 days	243 01 days, retrograde	23 hours, 56 min.	24 hours, 37 min.	9 hours, 56 min.	10 hours, 40 min.	17 hours, 14 min.	16 hours, 6 min.	6.39 days, retrograde
[illegible]	0.0	177.3	23.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Inclination of Orbit to Ecliptic (Degrees)	7.0	3 39	0.0	1.85	1.31	2.49	0.77	1.77	17.15
[illegible]	0.206	0.007	0.017	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Equatorial Diameter									
Kilometers	4,878	12,104	12,755	6,790	142,796	120,660	51,118	49,528	2,300 (Appx.)
Miles	3,031	7,521	7,926	4,219	88,729	74,975	31,763	30,775	1,429 (Appx.)
[illegible]	Essentially none	Carbon dioxide	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Satellites	None	None	1	2	16	18	15	8	1
[illegible]	None	None	None	None	1	[illegible]	[illegible]	[illegible]	[illegible]

*Periods are given in Earth time.

Despite their efforts to peer across the vast distances of space through an obscuring atmosphere, scientists of the past had only one body they could study closely — Earth. But since 1959, spaceflight through the solar system has lifted the veil on our neighbors in space.

We have learned more about our solar system and its members than anyone had in the previous thousands of years. Our automated spacecraft have traveled to the Moon and to all the planets beyond our world except Pluto; they have observed moons as large as small planets, flown by comets and sampled the solar environment. Astronomy books now include detailed pictures of bodies that were only smudges in the largest telescopes for generations. We are lucky to be alive to see these strange and beautiful places and objects.

The knowledge gained from our journeys through the solar system has redefined traditional Earth sciences like geology and meteorology and spawned an entirely new discipline called comparative planetology. By studying the geology of planets, moons, asteroids and comets, and comparing differences and similarities, we are learning more about the origin and history of these bodies and the solar system as a whole.

We are also gaining insight into Earth's complex weather systems. By seeing how weather is shaped on other worlds and by investigating the Sun's activity and its influence throughout the solar system, we can better understand climatic conditions and processes on Earth.

We will continue to learn and benefit as our automated spacecraft explore our neighborhood in space. One current mission is mapping Venus; others are flying between worlds and will reach the Sun and Jupiter after complex trajectory adjustments. Future missions are planned for Mars, Saturn, a comet and the asteroid belt.

We can also look forward to the time when humans will once again set foot on an alien world. Although astronauts have not been back to the Moon since December 1972, plans are being formulated for our return to the lunar landscape and for the human exploration of Mars and even the establishment of martian outposts. One day, taking a holiday may mean spending a week at a lunar base or a martian colony!

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL 410-34-1 6/91